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Geology and geochemistry-based metallogenic exploration model for the eastern Tethys Himalayan metallogenic belt, Tibet

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Metallogenic prediction model based on geological conditions and geochemical anomalies of CoDA, eastern of the Tethys Himalayan metallogenic belt, China

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Abstract:	<p>The Tethys Himalaya is the fourth metallogenic belt discovered in the Tibet Plateau and is mainly composed of chromite, Au and Sb-polymetallic deposits. The belt has experienced a series of complex tectonic evolution–magmatism events, such as the break-up, subduction, collision, detachment and obduction of the East Gondwana continent, which has produced unique mineralization. Limited understanding remains in some areas, such as the confusion of genetic types of deposits, the unclear relationship between tectonic evolution–magmatism and regional mineralization, and as a result there is no clear direction for further geological exploration at most of the mineralization occurrences. Based on the long-term research and exploration work in this area, as well as investigation of the metallogenic regularity of various deposits in surrounding regions, three main deposit types (ophiolite chromite deposit, orogenic Au deposit and hydrothermal-vein Sb-polymetallic deposit) and two types of predicted deposits (island arc type porphyry Cu–Au deposit and Sn deposit related to leucogranite) are proposed. This study summarizes the relationship between tectonic evolution–magmatism and mineralization, and establishes the time–space framework of regional mineralization in eastern of the Tethys Himalayan metallogenic belt.</p>
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Metallogenic prediction model based on geological conditions and geochemical anomalies of CoDA, eastern of the Tethys Himalayan metallogenic belt, China

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Abstract

The Tethys Himalaya is the fourth metallogenic belt discovered in the Tibet Plateau and is mainly composed of chromite, Au and Sb-polymetallic deposits. The belt has experienced a series of complex tectonic evolution–magmatism events, such as the break-up, subduction, collision, detachment and obduction of the East Gondwana continent, which has produced unique mineralization. Limited understanding remains in some areas, such as the confusion of genetic types of deposits, the unclear relationship between tectonic evolution–magmatism and regional mineralization, and as a result there is no clear direction for further geological exploration at most of the mineralization occurrences. Based on the long-term research and exploration work in this area, as well as investigation of the metallogenic regularity of various deposits in surrounding regions, three main deposit types (ophiolite chromite deposit, orogenic Au deposit and hydrothermal-vein Sb-polymetallic deposit) and two types of predicted deposits (island arc type porphyry Cu–Au deposit and Sn deposit related to leucogranite) are proposed. This study summarizes the relationship between tectonic evolution–magmatism and mineralization, and establishes the time–space framework of regional mineralization in eastern of the Tethys Himalayan metallogenic belt.

Based on improved knowledge of relative geochemical signatures obtained from

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compositional data analysis (CoDA) combined with geological knowledge, nine groups of compositional balances have been obtained, identifying sedimentary strata, accretionary wedge structure, leucogranite, mafic-ultramafic rocks, chromite mineralization, Au mineralization and Sb-polymetallic mineralization. This study establishes the metallogenic prediction model, and predicts the regional exploration direction through geological information and identification of geochemical anomalies. It is suggested that the ophiolitic belt, with a length of 50 km in the Nedong area, is very conducive to the exploration of chromite deposits; the Au-Cu-Mo high value anomaly area in Qonggyai-Qusum area has the prospect of exploration of orogenic Au deposits; the Au-Cu-Mo high value anomaly area in Nianzha, Sangri and Gyaca areas is the key exploration target of "Xiongcun-type" island arc type porphyry Cu-Au deposit; the deep direction of Sb-polymetallic deposit and the inner-outer contact zone of Lhozhang and Cuonadong leucogranite may be the important breakthrough of Sn (Be-U) deposit.

Keywords: Geology; Compositional data analysis; Regional metallogeny; Metallogenic prediction model; Tethys Himalaya

1. Introduction

The Tethys Himalayan metallogenic belt is located between the Indus-Yarlung Zangbo suture zone and the Southern Tibet Detachment System fault (Fig. 1a). It is an important part of the Indo-Eurasian continent collisional foreland fold-thrust belt, and it is also another Cr, Au and Sb-polymetallic metallogenic belt discovered in the Tibet Plateau after the Sanjiang Cu (Mo), Gangdese Cu-Mo and Bangong-Nujiang Cu-Au metallogenic belt. The resources of chromite in the Luobusha-Xiangkashan-Kangjinla area in the belt account for more than 40% of the total amount of chromite in China (Fig. 1b; Yang et al., 2018), and that, in the Zhaxikang-Keyue-Yufeng area, the metal resources of Sb have been proved to be more than 200,000 tons, and Pb + Zn has reached 2 million tons (Fig. 1b; Wang et al., 2012). In addition, a large number of medium-sized Au deposits have been found in the area (Fig. 1b; Yang et al., 2009; Zhai et al., 2014). The special deposit types and element assemblages in the Tethys Himalayan belt are closely related to the complex tectonic evolution-magmatic activities. However, the metallogenesis, regional metallogenic regularity and metallogenic prediction of the deposits in this area are still at a low level. For example, there is a dispute between orogenic-type and carlin-type deposits for gold deposits (Yang et al., 2006; Zhai et al., 2014; Zheng et al., 2007), and between SEDEX-type and hydrothermal-vein-type for Sb-polymetallic deposits (Wang et al., 2012; Zheng et al., 2012). Therefore, the continuous summary of regional metallogenic regularity is of great significance for the research and exploration of the deposit.

In terms of regional exploration work, in addition to continuous theoretical research, geochemical methods are also very important. In particular, geochemical exploration is essential prior to other exploration methods in this shallow covered area of Tibet Plateau, which has been confirmed in most of the discovered deposits (Cheng et al., 2001; Du et al., 2001; Liu et al., 2018; Yang et al., 2017). However, the anomalies obtained by different geochemical data processing methods are often quite different. The elemental associations used by traditional geochemical processing method is mainly composed of a few ore-forming elements, and the anomalies of several single elements obtained are mainly used for interpretation of mineralization, and the

anomalies are often scattered (Sun et al., 2016; Zheng et al., 2014). The use of Compositional data analysis (CoDA) for the analysis of the geochemical data in this study has informative results for exploration in the Jiama ore district (Zheng et al., in press), and has the potential to apply this method to regional prediction.

Compositional data are subject to the condition that the sum of the parent variables in any item is constant (closure effect), imposing a linear restraint which suppresses positive and increases negative covariance (Chayes, 1960), resulting in the issue of ‘spurious correlation’, as shown by Karl Pearson back in 1897 (Pawlowsky-Glahn, 2011; Pearson, 1897). Substantial developments and understanding in compositional data analysis have taken place since the Aitchison geometry was proposed (Aitchison, 1982; 1986; Egozcue et al., 2018; Pawlowsky-Glahn, 2011; Pawlowsky-Glahn et al., 2015; Van den Boogaart and Tolosana-Delgado, 2013). Compositional data analysis method is used to identify anomalies associated with stratigraphy, structures, magmatic rocks, distribution range of alteration and mineralization, which promotes better integration of geochemical anomalies and geological information.

This study establishes the regional metallogenic prediction model for the eastern part of the Tethys Himalayan metallogenic belt by summarizing the ore-control geological conditions and regional metallogenic regularity and integrating the geochemical anomalies obtained from CoDA.

2. Geological background

2.1 Structure

From north to south, the Qinghai–Tibet Plateau is divided into four terranes by Jinshajiang suture zone, Bangong–Nujiang suture zone and Indus–Yarlung Zangbo Suture Zone, which are Songpan–Ganzi terrane, Qiangtang terrane, Lhasa terrane and Himalayan terrane. The Himalayan terrane can be further divided into Tethys Himalaya, Higher Himalaya and lesser Himalaya by Southern Tibet Detachment System fault, Main Central Thrust and Main Boundary Thrust, and the south of Main Boundary Thrust is Indian plate (Fig. 1a; Pan et al., 2004; Yin et al., 2000; Yin, 2006). This study area is located in the eastern part of the Tethys Himalaya. According to the Lazi–Qiongdongjiang suture zone, Lhunze fault and Lhozhag–Cuonadong fault, it can be divided into Langjiexue accretionary wedge, Nieru thrust structural belt, Lhunze–Comai–Nagarze fold belt and Lakang thrust structural belt from north to south (Fig. 1b). In addition to abundant faults and fold structures, the area also has a unique metamorphic core complex domes belt. More than ten bead-like metamorphic core complex domes have been found in the Tethys Himalayan belt (Beaumont et al., 2004; Zhang et al., 2012). In this study area, there are two outcrops, i.e. Yardo and Ramba dome, both located near the late north–south tensional fault zone. The metamorphic core complex domes are closely related to the late structure (Fig. 1b; Aoya et al., 2005). The Tethys Himalayan dome is composed of Paleozoic and Precambrian greenschist to granulite facies metamorphic rocks and Eocene–Miocene leucogranite (Lee et al., 2004; 2006; Zhang et al., 2012).

2.2 Stratigraphy

The stratigraphy in the study area are mostly contacted and divided by faults. The Proterozoic strata are mainly exposed in the Higher Himalayan area south of Southern Tibet Detachment System and the metamorphic core complex dome, and the lithology is plagioclase gneiss, quartz schist and granulite. The Paleozoic strata are mainly phyllite, quartz schist, hornblende schist and

marble, which are overlaid on the Proterozoic strata by fault contact. In the Permian, only a small area of the Karela Formation is exposed in the south of the Ramba dome (Fig. 1b), and the lithology is calcareous phyllite and crystalline limestone. Triassic strata belong to Nieru Formation, mainly distributed in the west of the study area and between Lazi–Qiongduojiang suture and Lhunze fault (Fig. 1b), and the lithology is mainly lithic quartz sandstone with local sericite slate. The Jurassic strata in this area mainly consist of four Formations, which are the Ridang Formation, the Lure Formation, the Zhela Formation and the Weimei Formation from lower to upper. The main lithology is carbonaceous–calcareous slate and siltstone with tuff and thin limestone, which are the main ore-bearing formation of Sb-polymetallic deposits in this area. Sangxiu Formation is a special stratum in this area, which is just in the Jurassic/Cretaceous boundary in time, and its lithology is dominated by bimodal volcanic rocks, which are basalt–rhyolite combination, with conglomerate at the bottom. This stratum has important tectonic significance and is a sign of rift sedimentation (Liu et al., 2013; Zhu et al., 2007). In the Cretaceous strata, the Jiabula Formation and Zongzhuo Formation are exposed in the Lhunze–Comai–Nagarze fold belt (Fig. 1b), and the lithology is feldspathic quartz sandstone with argillaceous rock and shale. In the Lakang thrust structural belt, only the Lakang Formation is found (Fig. 1b), and the lithology is sericite slate, siltstone with thin limestone, and there are also many layers of basalt in the stratum, which also has certain tectonic significance (Yang et al., 2015). The Quaternary only occurs along the banks of the Yarlung Zangbo River and lakes (Fig. 1b).

The age of Langjiexue group is Triassic, but this group is a set of tectonic slices, which is an accretionary wedge formed during the subduction of the New Tethys ocean. The overall lithology is lithic feldspathic quartz sandstone mixed with many of ophiolite, volcanic breccia, basalt and other rock blocks (Li et al., 2016; Wang et al., 2016). There are a series of near East–West faults in the group. Recently, some researchers have proposed that Nieru thrust nappe should also be included in the accretionary wedge structure (Cai et al., 2016; Liu et al., 2020; Zhang et al., 2015).

2.3 Magmatic rocks

The magmatic rocks in the study area mainly include three parts. One is the ophiolite in the Indus–Yarlung Zangbo Suture Zone, which is a set of peridotite, gabbro, diabase and basalt assemblage. The zircon U–Pb age of the gabbro is 162.9 ± 2.8 Ma (Zhong et al., 2006), and the ophiolite age measured by McDermid et al. (2002) in Zedong area is between 152–156 Ma. Luobasha ophiolite belongs to the high titanium ophiolite suite of the oceanic tholeiite series, which is the remnant of the paleo-oceanic crust (Wang et al., 1987), and belongs to the product of the late Jurassic expansion of oceanic crust. The other is the Kerguelen–Bunbury–Comai Large Igneous Province (Coffin et al., 2002; Zhu et al., 2009), which is characterized by bimodal volcanic rocks of layered diabase–gabbro and veined rhyolite porphyry, and the rock ages are concentrated at 130–145 Ma (Lin et al., 2014; Zhu et al., 2009). There is no obvious fractionation of rare earth elements in basic volcanic rocks. Large ion lithophile elements such as Rb, Th, Ba, K, Sr are depleted, and high field elements such as Nb, Ta, Zr, Hf are weakly enriched. The Rb / Sr ratio is relatively low. The genesis of basic rocks is intraplate basalt series (Ma et al., 2018; Zhu et al., 2007; 2008; 2009). This stage also includes volcanic strata in the Sangxiu Formation. The last one is the leucogranite widely developed in southern Tibet, which is directly emplaced in the strata, and also emplaced from the core of metamorphic core complex dome (Fig. 1b). The rock age is

distributed in Eocene–Miocene (Lee et al., 2004; 2006; Zhang et al., 2012). The leucogranite in this area is mainly located in the Lhozhaq, Cuonadong area and center of Yardoi and Ramba dome (Fig. 1b). The rock type is two-mica granite and muscovite granite, characterized by high potassium calc-alkaline and strong peraluminous. It is obviously enriched with Rb, Th, U, K, Pb and other large ion lithophile elements, and depleted of Nb, Ta, P and other high field strength elements, and significantly depleted of Ba and Ti. The Rb / Sr ratio is very high, greater than 5 (Huang et al., 2013; Lin et al., 2016), suggesting that it is a product of crustal remelting, closely related to Sb-polymetallic deposits and Sn mineralization in the area (Cao et al., 2020; Zheng et al., 2017).

3. Mineralization types and features

According to the current research and exploration results in the study area, the main types of deposits are composed of three types, including ophiolite chromite deposits, orogenic Au deposits and hydrothermal-vein Sb-polymetallic deposits, although there are still some controversies on the genesis of the latter two types. In the following, a typical deposit will be selected according to three types to describe its geological and geochemical characteristics and discuss their mineralization.

3.1 Ophiolitic chromite deposit of Luobusha

The Luobusha–Xiangkashan–Kangjinla chromite ore-concentrated area is located in the east section of the Indus–Yarlung Zangbo suture zone. The ore-bearing rock is about 41 km long from east to west and 250 m–3.7 km wide from south to north, which is distributed in the form of "S" (Fig. 1b). The accumulated amount of chromite ore resource is more than 6 Mt, Cr₂O₃ @ 48%, PGE @ 0.5 ppm, and Cr / Fe ratio is more than 3.5 (Yang et al., 2018). The Luobusha deposit is located in the western part of the ore-concentrated area, and only the tertiary Luobusha group, which lies under the Indus–Yarlung Zangbo fault and dips to the south, composed of glutenite, is a set of Molasse Formation (Fig. 2a; Davis et al., 2004; Yin et al., 1999). The south side of the ore district is the accretionary wedge of Langjiexue group. The structure of the ore district is mainly north–south tensional–slip fault. The magmatic rocks in the area are bounded by the Indus–Yarlung Zangbo fault, with the Eocene granitic batholith of Gangdese in the north (Ji et al., 2009), the ophiolite in the south which belongs to the normal series of magnesian ultramafic rocks (M / F ratio is 8.8–11.6), and the overall attitude of the rock body dips to the south. The lithofacies of ultramafic rocks are zonation. In the north zone, there is mainly ultramafic–mafic melange, almost no mineralization; in the middle zone, there is dunite, with a small amount of chromite; in the South zone, there is augite peridotite, which is the main ore-bearing zone (Fig. 2a). The main alteration in the deposit is serpentinization.

The Luobusha deposit is composed of dozens of orebodies, most of which are less than 100 m in strike, and a few of which are more than 200 m. The geometry of the orebody is typical lenticular and podlike, dipping south (Fig. 2b). The ore is mainly of medium–dense disseminated structure, a few of which are massive, variegated and veined. The main metal mineral in the ore is picotite and a small amount of magnetite and goethite, and the main gangue mineral is olivine and serpentine, and a small amount of pyroxene and fuchsite.

The Luobusha deposit can be divided into three mineralization types. One is the early

magmatic fractional crystallization mineralization, which occurs in the dunite facies. The orebody is consistent with the primary flow structure, and the ore is mostly disseminated structure, showing a gradual transition relationship with the wall rock. The other is the late pressure filtration mineralization, which mainly occurs in the dunite facies, as well as in the augite peridotite. The geometry of orebody is convex lens, and the ore is commonly banded and patchy structure, which has a vague relationship with the wall rock and is formed by the short-distance migration and enrichment after the residual intergranular melt is pressed out. The third is the liquation–injection mineralization, which occurs in the augite peridotite. The orebody shape is controlled by faults, and the boundary between the ore and the wall rock is clear, which may be the deep liquation of ore-bearing magma and inject fracture zone (Zhai et al., 2011).

3.2 Orogenic Au deposit of Nianzha

The Nianzha Au deposit occurs in the southern boundary fault in the Indus–Yarlung Zangbo suture zone which is a fault system (Fig. 1b). The deposit is a new gold deposit discovered in recent years. The ore resource of the deposit is 7 Mt, Au @ 3.2 g/t, and oxidized ore is developed on the surface. The sedimentary strata in the ore district are rare. The marble xenoliths in the quartz diorite may be the residual by the subduction of Seamount. Langjiexue accretionary wedge is mainly distributed in the south of the ore district. The faults of ore-control are NW–SE in strike, and the overall dip NE in the upper part, and SW in the lower part, which have the characteristics of ductile–brittle deformation. In addition, some later NE–SW tensional–slip faults are also found in the area (Fig. 3a). The fold structure of the ore district is relatively developed, and the anticline structure controls Au orebody (Fig. 3b). A large number of ophiolitic remains are found in the suture zone and Langjiexue accretionary wedge, and early Cretaceous diabase dikes are also widely distributed in this area (see section 2.3). The most widely distributed magmatic rock in the ore district is quartz diorite in the north, with the same age of early Cretaceous (Mo et al., 2005), which is a granitoid formed in the subduction stage of the New Tethys ocean. A few Eocene granite dikes intrude into quartz diorite (Fig. 3a). The main alteration in the deposit is silicification, followed by carbonatization.

Four main orebodies are delineated in the Nianzha Au deposit. The orebodies occur in vein like faults in the contact zone between quartz diorite and ophiolite and are controlled by faults and anticline (Fig. 3b). The occurrence of orebody is consistent with that of fracture zone, and the length in strike is generally more than 500 m. The main gold-bearing minerals in the ore are limonite, pyrite and quartz, with a small amount of magnetite and carbonate minerals. The occurrence of gold in ore is mainly natural gold, which is wrapped in pyrite, limonite and quartz particles or filled in the cracks of these minerals. The particle size of gold is generally between 0.01–0.1 mm. The Au / Ag ratio in the ore is about 2.

The Nianzha Au deposit occurs near the north of Langjiexue accretionary wedge formed by the subduction of the New Tethys ocean. The ore-bearing fault is of ductile–brittle structure, and silicification and carbonatization alteration are developed. The results of fluid inclusions in quartz vein related to gold mineralization show that the ore-forming fluid composition is H₂O–NaCl–organic gas fluid. The fluid homogenization temperature is between 203°C and 347°C, and the salinity is 0.35 wt%–17.17 wt% NaCl equivalent. The $\delta^{18}\text{O}_{\text{fluid}}$ values of single quartz mineral are 0.15 ‰–10.45 ‰, and corresponding $\delta \text{D}_{\text{V-SMOW}}$ values are -173 ‰–96 ‰, and that, the $\delta^{13}\text{C}$

values are -17.6‰–4.7‰. Inclusion and isotopic data indicate the ore-forming fluids were a mix of metamorphic and sedimentary orogenic fluids with the addition of some meteoric and mantle-derived fluids (Zhang et al., 2017). These characteristics are similar to those of typical orogenic Au deposits (Groves et al., 1998; Goldfarb et al., 2001), indicating that the genetic type of Nianzha Au deposit should be orogenic Au deposit.

It is worth noting that hundreds of quartz veinlet Cu–Au mineralization can be discovered within about 1 km² of the eastern surface of the ore district. The metallogenic potential of porphyry Cu–Au deposit is discussed below (Fig. 3a).

3.3 Hydrothermal-vein Sb-polymetallic deposit of Zhaxikang

The Zhaxikang Sb-polymetallic deposit is located in Lhunze–Comai–Nagarze fold belt, which is the largest economic deposit found in the Tethys Himalayan belt. The proven metal resources of Zhaxikang deposit are 0.13 Mt Sb, 1.3 Mt Pb + Zn, 63.5 Moz Ag (Tibet Huayu Mining Co., Ltd., 2015). The strata in Zhaxikang ore district are relatively simple, which is the lower Jurassic Ridang Formation, with the lithology of carbonaceous slate and meta quartz sandstone (quartzite in part, Fig. 4a), and thin limestone in part. The structure of the ore district is a S–N trending tensional–slip fault, which controls the occurrence of the orebody. The type of magmatic rocks exposed in the ore district is relatively diverse. The oldest rock is Cambrian gneissic granite (Fig. 4a), which is the magmatic response of the Indian continent to Pan-African event (Xu et al., 2005). The most widely distributed magmatic rocks are bimodal diabase and rhyolite porphyry assemblages, with the diagenetic ages of 133 Ma ± and 135 Ma ± (Yang et al., 2014; Lin et al., 2014), which are part of the Kerguelen–Bunbury–Comai Large Igneous Province (Zhu et al., 2009). In addition, there are a few diorite dikes in the area. The alteration of the wall rock in the ore district is mainly silicification and Fe–Mn carbonatization, which are related to Sb mineralization and Pb–Zn mineralization respectively. Sericitization and chloritization can also be seen locally.

There are two orebodies in Zhaxikang deposit, No. V and VI (Fig. 4a), of which No. V orebody is the largest, accounting for 90% of the resources. No. V orebody occurs in the fault fracture zone in vein and lens shape, and the occurrence is basically the same as the fault. The length reaches 1200 m in strike, dips to the west, and the dip angle changes between 45°–70° (Fig. 4b). The typical ore structures are breccial, banded and veined. The main metallic minerals in the ore are stibnite, galena, sphalerite, a small amount of freibergite and boulangerite, and the non-metallic minerals are quartz and Fe–Mn carbonate minerals. Mineralization in the deposit has obvious zonation, from shallow to deep, Sb (Ag) → Pb + Ag (Zn + Sb) → Zn + Pb (Ag + Cu) (Zheng et al., 2017).

The genesis of Zhaxikang deposit is the most controversial in the Tethys Himalayan belt. The main viewpoints are divided into two types. The researchers who advocate the exhalation sedimentation mineralization believe that there are two mineralization processes in Zhaxikang. The early exhalation sedimentation forms Fe–Mn carbonate–sulfide mineral assemblages and Pb–Zn–Ag–Mn–Fe mineralization, and the later is hot spring mineralization, forming quartz–calcite–sulfide mineral assemblages and Sb–Hg mineralization (Zhang et al., 2010; Zheng et al., 2012; Zhu et al., 2012). The researchers who advocate hydrothermal mineralization believe that the orebody is strictly controlled by faults, with obvious breccial, miarolitic and veined ore structure, and

diabase can be one of the breccias (Fig. 4b, indicating that the mineralization age must be later than 133 Ma). Microscopic identification also found a wide range of metasomatic and residual textures related to hydrothermal metasomatism (Wang et al., 2012). The mineralization is characterized by low temperature and high temperature element zonation from shallow to deep, and the Sn content of more than 600 ppm has been measured in the single mineral of sphalerite in the deep (Zhang et al., 2016). It is proposed that the Zhaxikang deposit is a hydrothermal-vein type polymetallic deposit related to the genesis of the leucogranite in the south of the Cuonadong (Lin et al., 2016), and it is considered that the Sn orebody may be found in the deep or peripheral (Zheng et al., 2017). Recent geological exploration results also confirm the prediction (Cao et al., 2020; Li et al., 2017).

4. Multi-element geochemical signatures

4.1 Geochemical data

The geochemical dataset used in this study was collected via stream sediment sampling as part of the “Regional Geochemistry National Reconnaissance (RGNR) Project” which was initiated in 1979 and has now covered more than 7 million km² of China. The sample density is 1 per 7 km², and a total of 9,165 samples are included in this research. Samples have undergone multi-element analysis of 39 elements (including Bi, Cu, P, La, Li, Ag, Sn, Au, Mo, Th, U, W, Sb, Hg, Mn, Cr, Sr, Nb, Pb, Ni, Ti, Y, Cd, Co, Ba, Be, V, Zn, B, As, Zr, F, Fe₂O₃, K₂O, CaO, MgO, Na₂O, Al₂O₃, SiO₂) (Xie et al., 1997). The 39 elements were analysed by various methods including ICP-MS, XRF and ICP-AES. The specific test methods, detection limits, quality control and other information corresponding to each element have been published by Wang et al., 2007, Xie et al., 2008 and Xie et al., 1997 and are not repeated here.

4.2 Methodology

This study uses a knowledge-driven Compositional Data Analysis (CoDA) framework to investigate the geochemical data which includes the use of isometric log-ratio transformations (ilr), and sequential binary partition (SBP). CoDaPack software (Comas-Cufí et al., 2011), developed by the Research Group in Statistics and Compositional Data Analysis at University of Girona, is used in this analysis.

4.2.1 Logratio transformation

Within compositional theory (Aitchison, 1982; 1986), the additive log-ratio (alr) (Aitchison, 1986), the centered log-ratio (clr) (Aitchison, 1986), and the isometric log-ratio (ilr) (Egozcue et al., 2003; Filzmoser et al., 2012) transformations have been proposed to deal with the data ‘closure problem’ which can be used to transform raw data (e.g. geochemical data) from the ‘simplex’ to ‘Euclidean space’.

The D-part compositional data $x = (x_1, x_2, \dots, x_D)$, the alr [Eq. (1)], clr [Eq. (2)] and ilr [Eq. (3)] transformation of each part x_i ($i = 1, 2, \dots, D$) can be expressed as follow:

$$y_i = \log \frac{x_i}{x_D} \quad (i = 1, 2, \dots, D - 1) \quad (1)$$

$$y_i = \log \frac{x_i}{\sqrt{\prod_{i=1}^D x_i}} \quad (i = 1, 2, \dots, D) \quad (2)$$

$$y_i = \sqrt{\frac{D-i}{D-i+1}} \log \frac{x_i}{\sqrt{\prod_{j=i+1}^D x_j}} \quad (i = 1, 2, \dots, D-1) \quad (3)$$

Each of these three transformations has advantages and disadvantages. The alr is relatively straightforward to apply but the choice of denominator can be arbitrary. The clr transformation is straightforward but results may be affected by data collinearity as the sum of the clr-transformed data is zero. The ilr transformation is an orthogonal transformation and forms one-to-one relations between the Aitchison geometry on the simplex and the standard Euclidean geometry, with excellent geometrical properties, but results can be difficult to interpret (Filzmoser et al., 2012; Wang et al., 2014).

4.2.2 Sequential binary partition (SBP)

The Sequential binary partition (SBP) approach is proposed as a tool for compositional data analysis for dimension reduction through orthonormal basis transformation (Egozcue and Pawłowsky-Glahn, 2005).

The key of the SBP approach is the design of ilr-coordinates or compositional balances. Balances are particular ilr-coordinates with orthonormal bases which can be interpreted in the D-1 dimension real space as ratios of elemental associations (Egozcue et al., 2003; Petrik et al., 2018). To deal with D-parts compositional vectors $[x_1, x_2, \dots, x_D]$ in the simplex space, the first-order binary partition consists of making two groups of parts; the second-order partition is obtained by subdividing one of the first-order groups into two groups; the procedure is iterated until all groups contain only a single part. The number of binary divisions of a group to attain the end of the process is D-1, and this D-parts dataset has already been separated into non-overlapping D-1 groups or balances (subcompositions) of parts (Egozcue and Pawłowsky-Glahn, 2005; Liu et al., 2019).

The formula of compositional balances calculation is shown below [Eq. (4); Egozcue and Pawłowsky-Glahn, 2005; Petrik et al., 2018]:

$$z_i = \sqrt{\frac{rs}{r+s}} \ln \frac{(\prod_{+} x_j)^{1/r}}{(\prod_{-} x_k)^{1/s}} \quad \text{for } i = 1, 2, \dots, D-1; j = 1, 2, \dots, r; k = 1, 2, \dots, s \quad (4)$$

where $\prod_{+} x_j$ is the product involves r positive parts coded with $+$ in the i -th order partition, while $\prod_{-} x_k$ is the product involves s negative parts coded with $-$ in the i -th order partition, respectively.

4.3 Knowledge-driven ilr Balances design and mapping

In terms of geochemical compositional data, each compositional balance can be seen as a meaningful log-contrast with different data- or knowledge-driven elements associations (McKinley et al., 2016), where data-driven methods include hierarchical clustering, k-means, and so on, while knowledge-driven elements associations depend on the deep understanding in the geology and geochemistry background of the certain research area. Therefore, the compositional balance is a reasonable way to extract geochemical associations and can provide an interpretation

for the underlying geological, environmental and metallogenic framework.

According to the geological background, mineralization types and geochemical survey, some knowledge can be found. The element association K_2O-Na_2O can be seen as sandstone signature; the association $Co-V-Mn-CaO-Ti$ usually has a high value in black rock series; accretionary structure zone take a high value of Al_2O_3 ; leucogranite is a main type of acid rock, and causes $Pb-K_2O-Th-U$ enrichment; mafic-ultramafic rocks include peridotite, diabase has a high value of $Cr-Ni-Ti-MgO$; geochemical association $Cr-Ni$ can indicate Chromite mineralization; $Au-Cu-Mo$ can indicate Au and Cu-Au mineralization; $Hg-Sb-Pb-Ag-Zn-Cd-As$ is a useful geochemical signature of Sb-polymetallic mineralization and $Sn-Be-Li-B-F-Nb$ can reflect the location of $Sn(Be)$ mineralization. Meanwhile, taking the element depletion association as a “contrast” for each enrichment association above to design 9 ilr balances showed in Table.1. Corresponding ilr balance maps (Fig.5) generated by Equation (4) are log-contrast between two groups of parts within the Table. So every ilr balance may have a valid meaning for interpretation.

5. Discussion

5.1 Geological conditions for ore-control

For the chromite deposits in this area, the ophiolitic remains in the plate suture zone are important exploration directions, while the dunite facies and augite peridotite facies in the ophiolite are important targets for chromite deposit, and the enrichment degree of chromite is often strongly related to the alteration degree of serpentinization. The existence of liquation-injection mineralization in Luobusha indicates that the formation of chromite is not completely controlled by the differentiation-crystallization of ultramafic rocks, and faults are more important for the formation of chromite under the condition of obduction and emplacement mechanism similar to that of Indus-Yarlung Zangbo ophiolite.

The accretionary wedge / accretionary terrane of subduction suture zone is undoubtedly an important tectonic condition for the formation of orogenic Au deposits (Groves et al., 1998; Goldfarb et al., 2001). Therefore, Langjiexue Group including part of Nieru Formation are the favorable place for the formation of orogenic Au deposits such as Nianzha, Bangbu and Chalapu. Where affected by the accretionary wedge structure, it can also form orogenic Au deposits, such as those in Nagarze area, but the scale of the deposits is small. It is also important for the formation of orogenic Au deposits that ore-control faults have the dual ductile-brittle properties. The data of fluid inclusions and isotopes of deposits such as Nianzha and Bangbu indicate that the fluid properties are dominated by metamorphic fluid as well as the addition of mantle-derived fluid (Zhang et al., 2017). This extensive magmatic activity is also favorable for the formation of deposits. In the accretionary wedge structure of the study area, except orogenic Au deposits, it is also very important to estimate the metallogenic potential of porphyry $Cu-Au (Mo)$ deposits, and the key issue is, for example, whether the Cretaceous quartz diorite in Nianzha area is the continental arc granite or the intra-oceanic arc granite. If it is the intra-oceanic arc granite and the quartz diorite is spliced on the Lhasa terrane as a accretionary terrane, it is very likely to discovery the "Xiongcu-type" porphyry $Cu-Au$ deposit (Tang et al., 2015). Fortunately, it has been found that the early Cretaceous quartz diorite was formed in the intra-oceanic arc environment in the

Zhongba and Nedong area of the Indus–Yarlung Zangbo suture zone (Aitchison et al., 2000; Dai et al., 2011).

The Sb-polymetallic deposits in this area are mainly distributed in the Lhunze–Comai fold belt, and there are also a few mineral occurrences in the Lakang thrust belt in the south. The strata related to Sb-polymetallic deposits are mainly the black rock series (carbonaceous slate), which may provide some metal sources for the formation of the deposits (Li et al., 2014). Faults control the deposit, and ore-bearing faults are generally characterized by tensional–slip. Regional leucogranite provides an important material source for mineralization (Duan et al., 2016). According to the Sn (Be) mineralization which has been found in the contact zone of the leucogranite in the Cuonadong (Cao et al., 2020; Li et al., 2017), the periphery of Zhaxikang ore district, and in Nepal (Mitchell et al., 1976), these Sb-polymetallic veins may only be the medium–low temperature mineralized body around the real Sn deposit, which is very similar to Xianghualing Sn deposit in Hunan Province and Dachang Sn deposit in Guangxi Province, China (Chen et al., 1988; Du, 1983).

5.2 Tectonic evolution-magmatism and regional metallogeny

The earliest tectonic and magmatic activity found in the Tethys Himalaya is Cambrian, which is a response to Pan-African orogenic events. However, whether there is a metallogenic response similar to the Central African Copperbelt has not been found. At present, the earliest mineralization recorded in this area is chromite deposit in the Indus–Yarlung Zangbo suture zone, which was formed in the late Jurassic with the background of the initial break-up of the New Tethys ocean basin (McDermid et al., 2002; Zhong et al., 2006). The mechanism of the reverse location of chromite-bearing ophiolite and the molasse formation of the underlying Luobusha Group on the Gangdese batholith is the obduction of the Indian terrane towards the Lhasa terrane during the late collision–detachment stage (Fig. 6; Wang et al., 2000; Wang et al., 2015).

In the early Cretaceous, under the action of Kerguelen mantle plume, the Indian terrane disintegrated from the East Gondwana continent, and the area began to be in rift environment, with the development of large-scale bimodal volcanic rocks and the formation of Kerguelen–Bunbury–Comai Large Igneous Province (Coffin et al., 2002; Zhu et al., 2009), whether there are deposits related to intra-continental rifting environment or hot spot activity in this stage remains to be studied, such as Sullivan-type Pb–Zn deposit in British Columbia, Sn–Nb–U deposit related to peralkaline granite in Jos Plateau of Nigeria, Cr–Ni–Pt–Cu deposit in layered mafic–ultramafic rocks in South Africa–Zimbabwe, etc. (Mitchell et al., 1976; 1981). At this time, however, the occurrence of small-scale intra-oceanic subduction in the New Tethys ocean and the formation of intra-oceanic arc rocks have been confirmed in some areas (Aitchison et al., 2000; Dai et al., 2011), which points out an important direction for the exploration of "Xiongkun-type" island arc porphyry Cu–Au deposit (Tang et al., 2015), such as the exploration targets in Nianzha ore district and some island arc quartz diorite in Nedong area.

Since Paleogene, with the occurrence of continent–continent collision in India–Lhasa terrane, the Langjiexue accretionary wedge in the Tethys Himalayan region has undergone strong thrust and compression, forming an orogenic Au deposit (Fig. 6). Subsequently, the occurrence of Southern Tibet Detachment System led to large-scale crustal plastic rheology and remelting in the Tethys Himalayan belt, forming a metamorphic core complex dome belt and a large-scale

leucogranite (Lee et al., 2004; 2006; Zhang et al., 2012), meanwhile, has also created a large number of hydrothermal-vein type Sb-polymetallic deposits in the Lhunze–Comai–Nagarze fold belt (Fig. 6). The Sn mineralization related to leucogranite may be an important exploration direction in the region and the Higher Himalayan belt in the future (Mitchell et al., 1981; Zheng et al., 2017).

5.3 Significance of geochemical anomalies

Identification of stratigraphy/lithology: Sedimentary rocks play an important role in some mineralization of the area, especially the black rock series play a certain role in controlling the formation of Sb-polymetallic deposits. According to lithology and sedimentary environment, sedimentary rocks in the study area are mainly divided into two categories: one is medium-coarse-grained lithic quartz sandstone formed in Triassic regressive / shallow sea environment, including Langjiexue Group and Nieru Formation; the other is black rock series formed in Jurassic–Cretaceous transgressive environment, mainly composed of carbonaceous slate and sericite slate (Gradstein et al., 2005). Balance 1 (B1) obtained by CoDA element combination is K_2O-Na_2O vs $As-Cd-Zn-Pb-Ag-Au-Hg-Sb-Fe_2O_3-Mo-W-Bi-Sn-Be-Cu-Cr-Ni-Ti-MgO-Li-B-F-Th-U-Ba-Nb-Sr-P-Al_2O_3-CaO-Co-V-Mn-La-Zr-Y-SiO_2$ (Table 1). The high value anomaly represents the alkalinity in the rocks, and clearly identifies the distribution area of Triassic sandstone (Fig. 5a), indicating that the source area of Triassic sandstone may be alkali rich non-orogenic granites, which is consistent with the stable continental environment of East Gondwana at this time (Frisch et al., 2011). In contrast, the high value anomaly of B2 ($Co-V-Mn-CaO-Ti$ vs $U-Ba$, Table 1) assemblage clearly reflects the distribution area of black rock series in the study area (Fig. 5b). The black rock series reflects the characteristics of rich organic matter in sediments in anoxic environment. It is a set of rock assemblages with reduced properties, which has always been very important for the formation of non-ferrous metals (Meyers et al., 1992).

Identification of accretionary wedge: There is always a dispute on the division of the southern boundary of the Langjiexue accretionary wedge in the study area. The key to the dispute is whether to take Lazi–Qionghuojiang suture zone as the boundary or Lhunze fault as the boundary, that is, the ownership of the Nieru thrust structural belt (Cai et al., 2016; Li et al., 2010; Tibetan Bureau of Geology and Mineral Resources, 1993; Wang et al., 2016; Webb et al., 2013). The results of element combination of B3 (Al_2O_3 vs CaO) show that (Table 1), the high value area obviously reflects the distribution range of accretionary wedge structure, including Nieru thrust structural belt (Fig. 5c). It indicates that Nieru thrust structural belt should belong to Langjiexue accretionary wedge, which is consistent with recent research results (Cai et al., 2016; Liu et al., 2020; Zhang et al., 2015). B3 does not reflect the distribution area of large area Nieru Formation in the west of Lhohzag. It also shows that the content of B3 reaction is obviously different from B1, mainly reflecting the range of accretionary wedge structural belt (Fig. 5c). The extensive greenschist facies alteration of accretionary wedge indicates that in the process of collisional orogeny, a large number of metasomatism dominated by metamorphic fluid is caused by compression, which forms aluminum rich silicate alteration (Wang et al., 2000). This is the basic reason that B3 can recognize the accretionary wedge structural belt.

Identification of leucogranite: The element combination of B4 ($Pb-K_2O-Th-U$ vs $Sr-P-Ti-$

Ba–Nb, Table 1) clearly reflects the distribution of leucogranite in the area, including Lhozha leucogranite with the largest distribution area, Cuonadong, and leucogranite in Yardoi and Ramba dome (Fig. 5d). This set of element assemblage is consistent with the geochemical characteristics and petrogenetic types of leucogranite in the study area, and belongs to the granite formed by crustal remelting (Huang et al., 2013; Lin et al., 2016; Liu et al., 2019; Zeng et al., 2011).

Identification of mafic to ultramafic rocks: Element combination of B5 (Cr–Ni–Ti–MgO vs As–Cd–Zn–Pb–Ag–Au–Hg–Sb–Fe₂O₃–Mo–W–Bi–Sn–Be–Cu–Li–B–F–Th–U–K₂O–Ba–Nb–Sr–P–Al₂O₃–CaO–Co–V–Mn–La–Zr–Y–Na₂O–SiO₂, Table 1) different from B4, it reflects the distribution range of mafic–ultramafic rocks, mainly including ophiolite in the Indus–Yarlung Zangbo suture zone, melange block in Langjiexue accretionary wedge, and the distribution area of volcanic rocks in Sangxiu Formation and some of the Lakang Formation (Fig. 5e).

Identification of chromite mineralization: On the basis of B5, this study chooses B6 (Cr–Ni vs Ti–MgO) element combination for further anomaly interpretation of mafic–ultramafic rocks (Table 1). It is found that the high value anomaly area well delineates the distribution area of chromite mineralization (Fig. 5f), which is an important set of element combination for identifying chromite mineralization in this area. It is worth noting that in addition to the Luobusha–Xiangkashan–Kangjinla ore concentration area and the anomaly are very corresponding to the past, the ophiolitic belt with a length of more than 50 km in Nedong area also shows very good chromite anomaly information (Fig. 5f), and at present dozens of mineral occurrences have been found in this area, which is worth further exploration.

Identification of Au (Cu) mineralization: The B7 element combination (Au–Cu–Mo vs Sb–Pb–Zn–Ag, Table 1) obtained in this study is a group of important geochemical anomalies based on the understanding of regional mineralization. On the one hand, the anomalies of this group have well delineated the scope of gold mineralization, but different from other research methods (Sun et al., 2016), the high values of Au–Cu–Mo have several abnormal areas near the suture zone, such as Nianzha Au ore district, Sangri and Gyaca area (Fig. 5g). These areas have revealed copper and gold mineralization in Early Cretaceous quartz diorite (Fig. 3a; Aitchison et al., 2000; Dai et al., 2011), which is possible that the intra-oceanic island arc was spliced onto the Lhasa terrane as a accretionary terrane. Therefore, there is a great potential to find "Xiongcu-type" island arc porphyry Cu–Au deposits in these anomaly areas. In terms of the exploration direction of individual Au deposits, the high value anomaly delineated by Qonggyai–Qusum area is likely to be similar to the discovered Bangbu–Xigong–Muda gold concentration area (Fig. 5g), and multiple mineral occurrences are also found on the surface, which is worthy of further work.

Identification of Sb-polymetallic mineralization: Element combination of B8 (Hg–Sb–Pb–Ag–Zn–Cd–As vs Au–Fe₂O₃–Mo–W–Bi–Sn–Be–Cu–Cr–Ni–Ti–MgO–Li–B–F–Th–U–K₂O–Ba–Nb–Sr–P–Al₂O₃–CaO–Co–V–Mn–La–Zr–Y–Na₂O–SiO₂, Table 1) reflects the distribution range of Sb-polymetallic mineralization in the study area, and the anomaly areas with high value over 0.72 corresponds very well to the two main ore concentration areas Zhaxikang–Keyue–Yufeng and Yongri–Rangla–Cheqiongzhubu (Fig. 5h), indicating the applicability of the anomaly combination. However, it is difficult to discover this type of deposit with a certain scale in other places according to the anomaly distribution map.

Identification of Sn (Be) mineralization: As mentioned above, Sn mineralization has

important exploration significance in the Tethys Himalayan belt and even the whole Himalayan fold orogenic belt (Cao et al., 2020; Li et al., 2017; Mitchell et al., 1981; Zheng et al., 2017). The B9 (Sn–Be–Li–B–F–Nb vs As–Cd–Zn–Pb–Ag–Au–Hg–Sb–Fe₂O₃–Mo–W–Bi–Cu–Cr–Ni–Ti–MgO–Th–U–K₂O–Ba–Sr–P–Al₂O₃–CaO–Co–V–Mn–La–Zr–Y–Na₂O–SiO₂) obtained in this study, high value anomalies delineate four major anomaly areas that are closely related to leucogranite (Fig. 5i), which is also consistent with the conclusion of regional metallogenic regularity summarized in the previous paper. Sn mineralization (skarn type, quartz vein type, greisen type, etc.) related to leucogranite may be an important exploration direction in this area and Himalayan orogenic belt in the future (Mitchell et al., 1981; Zheng et al., 2017).

5.4 Metallogenic prediction model

Based on the analysis of three main deposit types (ophiolite chromite deposit, orogenic Au deposit and hydrothermal-vein Sb-polymetallic deposit) and two types of predicted deposits (island arc type porphyry Cu–Au (Mo) deposit and Sn (Be–U) deposit related to leucogranite, the relationship between tectonic evolution–magmatism and metallogeny in this area is summarized, and the time and space of regional mineralization is established. The regional metallogenic prediction model is established by combining geological information with geochemical anomalies based on CoDA method (Fig. 6). On this basis, this study considers that the deposit types and areas worthy of further exploration are: (1) the ophiolitic belt with a length of 50 km in Nedong area is favorable for exploration of chromite deposits; (2) the Au–Cu–Mo high value anomaly area in Qonggyai–Qusum area has the prospect of exploration for orogenic Au deposits; (3) the Au–Cu–Mo high value anomalies in Nianzha, Sangri and Gyaca areas are the key exploration target areas of "Xiongcun-type" island arc porphyry Cu–Au deposit; (4) the deep part of Sb-polymetallic deposit and the inner–outer contact zone of Lhozhaq and Cuonadong leucogranite may be the important breakthrough of Sn (Be–U) deposit.

6. Conclusions

This study suggests that there are three main types of deposits in the Tethys Himalayan belt, including ophiolite chromite deposit, orogenic Au deposit and hydrothermal-vein Sb-polymetallic deposit. The ophiolite chromite deposit was formed in the early stage of the expansion of the New Tethys ocean basin. The main host rock is augite peridotite. Serpentinization is strongly related to mineralization and enrichment. The orogenic Au deposits are formed in the accretionary wedge structural belt. In the environment of intense compression during collision stage, the contact zone of sandstone–slate / ophiolite or ophiolite / quartz diorite is the main ore-bearing structure. The anticline controls the location of the Au orebody. The silicification and carbonatization are closely related to the gold mineralization. Hydrothermal-vein Sb-polymetallic deposits are mainly formed in Lhunze–Comai–Nagarze fold belt. The occurrence of orebodies is controlled by extensional–slip faults. The black rock series also controls the deposits. Silicification and Fe–Mn carbonatization are related to Sb mineralization and Pb–Zn mineralization, respectively.

The geochemical anomalies revealed through a combination of geological knowledge and compositional data analysis of geochemical data have enabled the interpretation of the distribution range and regularity of sedimentary strata, accretionary wedge structure, leucogranite, mafic–ultramafic rocks, chromite mineralization, Au mineralization and Sb-polymetallic mineralization

in the study area.

Based on the combination of geological information and analysis of geochemistry, it is considered that there may be two new types of deposits in the study area, island arc type porphyry Cu–Au (Mo) mineralization and Sn (Be–U) mineralization related to leucogranite

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Figure captions:

Fig. 1. (a) Tectonic sketch map showing location of the study area (after Pan et al., 2004; Yin et al., 2000). JS, Jinshajiang suture; LSS, Longmucuo–Shuanghu suture; BNS, Bangonghu–Nujiang suture; IYZS, Indus–Yarlung Zangbo suture; STDS, South Tibetan detachment system; MCT, Main Central Thrust; MBT, Main Boundary Thrust; ALT, Altyn Tagh fault; KF, Kunlun fault; KLF, Karakoram fault; JF, Jiali fault. TH, Tethys Himalaya; HH, Higher Himalaya; LH, Lesser Himalaya. (b) Generalized geological and deposits distribution map of the study area (after Pan et al., 2004). LQS, Lazi–Qionduojiang suture; LF, Lhunze fault; LCF, Lhozha–Cuonadong fault. Chromite deposits: LBS, Luobusha; XKS, Xiangkashan; KJL, Kangjinla. Au deposits: NZ, Nianzha; SHL, Shengla; KB, Kangbugunba; ND, Naodong; HW, Hawong; SL, Sheli; BB, Bangbu; XG, Xigong; MD, Muda; CLP, Chalapu. Sb-polymetallic deposits: ZXX, Zhaxikang; KY, Keyue; YF, Yufeng; GD, Gudui; MZL, Mazhala; ZG, Zhegu; YR, Yongri; RL, Rangla; CB, Cheqiongzhuobu.

Fig. 2. (a) Generalized geological map of Luobusha ore district. (b) Typical cross-section of Luobusha deposit.

Fig. 3. (a) Generalized geological map of Nianzha ore district. (b) Typical cross-section of Nianzha deposit.

Fig. 4. (a) Generalized geological map of Zhaxikang ore district. (b) Typical cross-section of Zhaxikang deposit.

Fig. 5. Geological information overlapped with ilr balances map. (a)~(i) correspond to the nine balances of B1 ~ B9, respectively.

Fig. 6. Metallogenic prediction model of the study area.

Deposit type	Ophiolitic chromite deposit	Orogenic Au deposit	Hydrothermal-vein Sb-polymetallic deposit
Tectonic position	IYZS	Langjiexue accretionary wedge	Lhunze–Comai–Nagarze fold belt
Sedimentary condition	No direct connection	Meta-sedimentary rocks / greenschist facies	Black rock series
Ore-control structure	Compressional fault	Ductile–brittle fault and anticline	Extensional–slip fault
Magmatic condition	Augite peridotite lithofacies, A small amount of dunite lithofacies	Less effect	Leucogranite
Alteration	Serpentinization	Silicification and carbonatization	Silicification and Fe-Mn carbonatization
Ore-forming elements	Cr (PGE)	Au (Ag)	Sb–Pb–Zn–Ag (Cu)
Mineral assemblage	Ore minerals: picotite; gangue minerals: olivine + serpentine	Ore minerals: limonite + pyrite; gangue minerals: quartz + calcite	Ore minerals: stibnite + galena + sphalerite + freibergite; gangue minerals: quartz + siderite + rhodochrosite
Stream sediment geochemistry	Lithologic anomaly: sandstone K ₂ O–Na ₂ O (+); black rock series Co–V–Mn–CaO–Ti (+)		
	Accretionary structure zone anomaly: Al ₂ O ₃ (+)		
	Leucogranite anomaly: Pb–K ₂ O–Th–U (+)		
	Mafic–ultramafic rocks anomaly: Cr–Ni–Ti–MgO (+)		
	Chromite mineralization anomaly: Cr–Ni (+)		
	Au mineralization anomaly: Au–Cu–Mo (+)		
	Cu–Au mineralization anomaly: Au–Cu–Mo (+) anomalies of accretionary terrane of intra-oceanic arc rocks		
	Sb-polymetallic mineralization anomaly: Hg–Sb–Pb–Ag–Zn–Cd–As (+)		
Sn (Be) mineralization anomaly: Sn–Be–Li–B–F–Nb (+)			

0 20 40 km

STDS, LCF, Be-Sn, ZK, LF, CLP, Yadoi Dome, LQS, BB, LBS, IYZS, MCT, MBT, NZ, Cu-Au?

Luobusha Group (E₁–N₁)
Jurassic strata
Cretaceous strata
Triassic strata
Sangxiu Formation (J/K)
Himalayan meta-sedimentary rocks (Pz + Pt)
Langjiexue Group (T)
Ophiolite (J₃)
Mafic dikes (K₁)
Quartz diorite (K₁)
Gangdese batholith (E_{1,2})
Leucogranite (E₂–N₁)
Paleo-Subduction slab

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Table

Table 1.docx

Conflict of Interest

No Conflict of Interest