Article

Genesis of the Baiyangping Cu–Co and Pb–Zn Mineralizations in Lanping Basin, SW China

Jiaxuan Zhu ^{1,*}, Hongyu Duan ^{1,*} , Lifei Yang ², Qi Chen ¹, Lijun Liu ¹, Kangxing Shi ¹, Jinlong Qian ¹, Qiaoxin Li ¹ and Rong Hu ¹

¹ State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing 100083, China; 3001190005@cugb.edu.cn (J.Z.); dirk@cugb.edu.cn (Q.C.); 17854286614@163.com (L.L.); shikx@email.cugb.edu.cn (K.S.); 2001200051@cugb.edu.cn (J.Q.); 2001200050@cugb.edu.cn (Q.L.); 2101210100@cugb.edu.cn (R.H.)

² School of Earth of Sciences, East China University of Technology, 418 Languang Road, Nanchang 330013, China; lfyang@ecut.edu.cn

* Correspondence: 3001200042@cugb.edu.cn; Tel.: +86-10-82323761; Fax: +86-10-82321006

Abstract: The Oligocene to Miocene Baiyangping Cu–Co and Pb–Zn mineralization was deposited during the collision of the India and Asia continents. The mineralization is hosted in veins in faulted carbonate and clastic rocks, which act as fluid pathways. A detailed fluid-inclusion analysis and C–O–S isotopic study are reported, focusing on the origin of the mineralizing fluids and mineralizing processes. The microthermometry of fluid inclusions hosted in quartz and carbonates indicate that the fluid peak temperature for both Cu–Co and Pb–Zn mineralizations ranges from 160 to 200 °C and from 120 to 160 °C, respectively. During these metallogenic hydrothermal events, salinity evolved from 2.7 wt% NaCl equiv to 24.8 wt% NaCl equiv. The $\delta^{34}\text{S}$ values measured on sphalerite and tennantite range from +5.2‰ to +9.5‰, which indicates that sulfur originated from a reservoir characterized by thermochemical sulfate reduction (TSR). The C–O isotopic values obtained from the carbonate samples suggest that the fluid mainly originates from basinal brines. The combination of C and S isotopic values of the Cu–Co and Pb–Zn mineralization indicate the sedimentary source of the basin. Mineralization is controlled by faults, thermochemical sulfate reduction, and the physicochemical conditions of the fluid.

Keywords: Baiyangping; base metals; C–O–S isotopes; fluid source and evolution; basinal brines

Citation: Zhu, J.; Duan, H.; Yang, L.; Chen, Q.; Liu, L.; Shi, K.; Qian, J.; Li, Q.; Hu, R. Genesis of the Baiyangping Cu–Co and Pb–Zn Mineralizations in Lanping Basin, SW China. *Appl. Sci.* **2022**, *12*, 2129. <https://doi.org/10.3390/app12042129>

Academic Editor: Nikolaos Koukoulas

Received: 19 November 2021

Accepted: 20 January 2022

Published: 18 February 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The classification of sediment-hosted Pb–Zn deposits consists of Mississippi Valley-type (MVT), vein-type, or clastic-dominated deposits. Sediment-hosted Pb–Zn deposits are major sources of Pb and Zn and significant sources of Ag and Ge, whereas Cu mineralization is generally rare yet economically important [1–5]. Such Pb–Zn deposits rich in Cu–Co and hosted in siliciclastic and dolomitic rocks often have mixed mineralizing fluid sources, such as basinal brines relating to magmatic–hydrothermal or metamorphic fluids [6–10].

The currently known sediment deposits include those located in the Otavi Mountain Land of Namibia; in the Goodsprings district of Nevada, America; and in the Leeuwbosch and Thabazimbi district of Cornwall [11–14]. The rarity of such types of sediment-hosted deposits appears to reflect a more complex genesis, which deserves detailed studies.

To distinguish the coexistence and precipitation mechanisms involved in the formation of sediment deposits, we chose to study the Baiyangping Cu–Co–Pb–Zn metallogenic district in the Mesozoic to Cenozoic Lanping Basin of SW China [15–18]. The mineralization is widespread in the central part of the basin, which is located within the eastern part of the Indian–Asian collisional zone (Figure 1).

Figure 1. Simplified geological maps: (a) Lanping Basin; reprinted with permission from Ref. [9], 2018 Wiley. (b) Baiyangping Cu–Co–Pb–Zn deposit; reprinted with permission from Ref. [10], 2016 Wiley.

The Baiyangping deposit, a typical sediment-hosted Cu–Co–Pb–Zn deposit that the homonymous metallogenic district is named after, is controlled by faults cutting through Middle Jurassic and Early Cretaceous siliciclastic and carbonate rocks. It is located at the intersection of the ESE-trending Wudichang and northerly trending Xiayanshan faults [18]. Previous studies on the Baiyangping Cu–Co–Pb–Zn deposit focused on its geology, mineralization, fluid inclusions, isotopes, and geochronology [19–23]. Despite extensive studies on the deposit, none of them have conclusively determined its genesis [24–26]. The mineralization in the area is considered to have been formed either after a magmatic–hydrothermal activity driven by concealed plutons or a focused influx of basinal brines originating from sedimentary sequences [24,26–28]. These opposing interpretations point to the necessity for a more integrated approach regarding the deposit’s genesis. Such a study requires a better understanding of the structural, lithological, and geochemical parameters controlling the deposit. Furthermore, knowledge of the genesis and ore-forming controllers for the Baiyangping polymetallic districts is considered essential in determining vectors for prospectors to find similar deposits in this tectonic setting, which extends to the north and south along the Cenozoic Tethys Orogen.

This paper reports an integrated study on the geological and isotopic characteristics of Cu–Co and Pb–Zn ores in the Baiyangping deposit, based on new data presented in this work and other published journals. The genesis of this mineralization is discussed in regard to its tectonic setting, source, deposition, and diagenesis.

2. Geology of the Baiyangping Deposit

The Lanping Basin is located in the central part of the Sanjiang Tethys Terranes and is bound by the Changning-Menglian suture to the west, and the Jinshajiang-Ailaoshan suture to the east [24,26,28]. The prominent structure in the Lanping basin is the northerly trending thrust fault belt (Figure 1b). The thrusts in the western part of the belt dip $\sim 30^\circ$ W, whereas those in the east dip $\sim 50\text{--}80^\circ$ E. In the region under investigation, the northerly trending thrust faults can be further divided into those trending NNW with a west inclination and those trending NNE with an east inclination, both of which have dip-angles over 60° . There are also ESE-trending strike-slip faults, which cut the above-mentioned faults. The Baiyangping deposit contains Pb–Zn and Cu–Co orebodies. The Cu orebodies are commonly hosted in Jurassic, Cretaceous, and Paleocene mudstones, whereas the Pb–Zn orebodies generally appear in Triassic limestones, Jurassic sandstones, and argillaceous limestones. The mineralization type of the deposit involves open-space filling and replacement of host rocks along different faults or within hydrothermal dissolution-collapse breccias. The ore minerals in the Baiyangping deposit include chalcocite, chalcopyrite, tennantite, galena, sphalerite, cobaltine, siegenite, arsenopyrite, argentite, kongsbergite with trace bournonite, orpiment, realgar, cerussite, and hemimorphite. The gangue minerals include quartz, calcite, ankerite, dolomite, and barite, and the alteration-related minerals consist of silica, sericite, carbonates, smithsonite, and epidote.

Two hydrothermal events have been identified in the area. The first one is characterized by early barren carbonate–quartz veins followed by Cu–Co mineralization within carbonate veins or as breccia cement (Figure 2a,b). This hydrothermal event is characterized by a variety of Cu and Co sulfides as well as sulfosalts including tennantite–tetrahedrite series, chalcopyrite, bornite, argentite, kongsbergite, cobaltine, siegenite, and Co-bearing arsenopyrite. Tennantite commonly replaces chalcopyrite along its margin (Figure 3a–c). The second hydrothermal event is dominated by Pb–Zn mineralization and is featured in carbonate veins with variable amounts of galena, sphalerite, tetrahedrite, bornite, and minor pyrite and pyrrhotite (Figures 2c,d and 3d). The chalcopyrite–tennantite–tetrahedrite–cobaltine stage is earlier than the sphalerite–galena stage.

Figure 2. Macroscopic features of ore samples: (a) warly calcite vein; (b) tennantite cementing brecciated carbonate (Cu–Co stage); (c) sphalerite–galena–dolomite mineral paragenesis (Pb–Zn stage);

and (d) galena–calcite vein within the wall rock (Pb–Zn stage). Abbreviations: Cal = calcite, Dol = dolomite, Gn = galena, Tnt = tennantite, and Sp = sphalerite.

Figure 3. Optical and scanning electron microscopy images of the main mineralization at the Baiyangping Cu–Co–Pb–Zn deposit showing (a) early chalcopyrite–tennantite–calcite paragenesis; (b) early chalcopyrite–tennantite–bornite–calcite paragenesis; (c) early cobaltite–tennantite–quartz paragenesis; and (d) late galena–sphalerite–pyrite–calcite paragenesis. Abbreviations: Bn = bornite, Cal = calcite, Ccp = chalcopyrite, Cob = cobaltine, Dol = dolomite, Gn = galena, Tnt = tennantite, Qzt = quartz, and Sp = sphalerite.

3. Analytical Methods

3.1. Samples

Samples were selected from the Baiyangping deposit at the 1200 and 1300 m levels and from outcrops at the elevation of ~1800 m. Samples were crushed and separated using a combination of heavy liquids, and magnetic and hand-picking techniques. The extracted minerals were then examined by X-ray diffraction to ensure sample purity.

3.2. Fluid Inclusions

Twenty-two samples were collected for fluid inclusion examination. Thin, polished sections were used to microscopically assess the characteristics of inclusions in quartz and carbonates for their relative age, shape, size, and style of distribution by a Zeiss microscope. Zeiss microscope produced by Carl Zeiss Microscopy GmbH company, jena, Freista at Thüringen, Germany. Microthermometric studies were conducted at the laboratory of China University of Geosciences in Beijing, Beijing, China, the fluid inclusion microthermometry was then conducted using a Linkam THMS 600. The fluid inclusions were heated at 0.2 °C/min and frozen at 0.1 °C/min. The measured indices consisted of the first ice-melting temperature (T_m) of carbonic hydrite (T_m, cl), the ice-melting temperature (T_m, ice), and the homogenization temperature (T_h). The salinity of the aqueous two-phase inclusions was calculated from the measured final melting temperature, using data for the NaCl–H₂O system from Bodnar et al. [25]. The salinity was calculated from the measured melting temperature of rock salt, applying the equations of Lecumberri-Sanchez et al. [29].

3.3. C–O Isotopes

Calcite crystals from the Pb–Zn and Cu–Co samples were selected by hand using a stereomicroscope and washed in distilled water. The samples were dried overnight in an oven at 60 °C and ground to powder using a mortar and pestle. Carbon and oxygen isotope measurements were made in the Laboratory of Environmental Isotope Geochemistry, Institute of Geology and Geophysics (CAS), Chinese Academy of Sciences. The MAT 253 stable isotope ratio mass spectrometer produced by Thermo Scientific in Waltham, MA, USA. During Gas Bench II carbonate preparation, approximately 150 µg of sample powder reacted with 100% phosphoric acid at 72 °C for 6 h. The carbon and oxygen isotope ratios of CO₂ were measured using a MAT-253 mass spectrometer with an accuracy greater than 0.1‰. After every six measurements, accuracy and precision were routinely checked by running NBS-19 carbonate criteria. Reproducibility for the carbon and oxygen isotopic compositions of apatite carbonate is better than ±0.1‰ and ±0.2‰, respectively. Pee Dee Belemnite (PDB) standard and Standard Mean Ocean Water (SMOW) were applied for the determination of carbon isotope ratios and oxygen isotope ratios.

3.4. S Isotopes

The sulfur isotope analysis in sphalerite and tetrahedrite was conducted in the Laboratory of Stable Isotope Geochemistry, Institute of Geology and Geophysics, Chinese Academy of Sciences. The MAT 253 stable isotope ratio mass spectrometer produced by Thermo Scientific in Waltham, MA, USA. The analysis was completed using 200 mesh pure samples, which were burned with CuO, Cu₂O, and V₂O₅ in an oven at 1000 °C under vacuum conditions. The released SO₂ was frozen in a liquid nitrogen trap. After low-temperature separation from other gases, the S isotope composition was measured using the Canyon Diablo Troilite (CDT) standard on a MAT-253 mass spectrometer with an analytical accuracy of ±0.2‰. The accuracy of conventional analysis of standard substance is ±0.2‰.

4. Results

4.1. Fluid Inclusion Data

A microscopic study revealed that primary fluid inclusions predominate over secondary inclusions, developing irregular, ovoid, and negative crystal shapes (Figure 4). Our study was focused on primary inclusions as defined by Roed-Der et al. [30]. The primary fluid inclusions consisted of two phases, including a liquid phase and vapor bubbles hosted in quartz, calcite, dolomite, and gypsum. The diameters of the two-phase inclusions are from 2 µm to 20 µm. A limited number of fluid inclusions has three phases including daughter crystals. The microthermometry data and calculated parameters of fluid inclusions are summarized and illustrated in Figure 5.

4.2. C–O Isotopes

Forty-four samples of carbonate minerals were used to determine the carbon and oxygen isotope values. The $\delta^{18}\text{O}_{\text{SMOW}}$ values of carbonates were calculated using the formula: $\delta^{18}\text{O}_{\text{SMOW}} = 1.03091 \times \delta^{18}\text{O}_{\text{PDB}} + 30.91$ [31]. The carbon and oxygen isotopic compositions are listed in Table 1. The $\delta^{13}\text{C}_{\text{PDB}}$ values in ankerite and calcite vary from −5.5‰ to +1.8‰. The $\delta^{18}\text{O}_{\text{SMOW}}$ values in ankerite and calcite vary from +12.2‰ to +20‰ (Table 1).

Figure 4. Photomicrographs showing the types and distribution of fluid inclusions in quartz from the Baiyangping Cu–Co–Pb–Zn deposit. (a–c) Liquid-rich two-phase inclusions in quartz; (d) liquid-rich two-phase inclusions in calcite.

Figure 5. Homogenization temperature (a) and salinity (b) histograms for all of the inclusion types from two hydrothermal events at the Baiyangping Cu–Co–Pb–Zn deposit.

Table 1. Carbon and oxygen isotopic compositions of carbonate minerals at the Baiyangping Cu–Co–Pb–Zn deposit.

Sample No.	Stage	Mineral	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{SMOW}}$
BYP15D02B11-2	Cu–Co stage	Calcite	−1.7	−11.3	+19.2
BYP15D02B2	Cu–Co stage	Calcite	−3.0	−11.2	+19.3
BYP15D03B1	Cu–Co stage	Calcite	−3.6	−13.3	+17.2
BYP15D03B12-1	Cu–Co stage	Calcite	−3.2	−12.6	+17.9
BYP15D03B12-2	Cu–Co stage	Calcite	−3.1	−12.5	+18.0
BYP15D03B7	Cu–Co stage	Calcite	−4.2	−15.3	+15.1
BYP15D03B11	Cu–Co stage	Calcite	−4.6	−12.7	+17.8
BYP15D02B14	Cu–Co stage	Ankerite	−3.0	−12.2	+18.3
BYP15D02B17	Cu–Co stage	Calcite	−5.5	−11.1	+19.4
BYP15D02B14-1	Cu–Co stage	Ankerite	−3.7	−13.4	+17.1
BYP15D03B11	Cu–Co stage	Calcite	−4.7	−12.7	+17.8

Table 1. Cont.

Sample No.	Stage	Mineral	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{SMOW}}$
BYP15D02B3	Cu–Co stage	Ankerite	−5.2	−10.3	+20.2
BYP15D03B2	Cu–Co stage	Calcite	−4.4	−12.4	+18.1
FLC15D01B1-1	Cu–Co stage	Calcite	−3.8	−16.7	+13.6
FLC15D01B1-2	Cu–Co stage	Calcite	−4.0	−16.7	13.6
FLC15D01B2-1	Cu–Co stage	Calcite	−3.3	−14.9	+15.5
FLC15D01B3-3	Cu–Co stage	Calcite	−3.9	−15.0	+15.4
FLC15D01B4	Cu–Co stage	Calcite	−4.1	−16.9	+13.4
FLC15D02B10	Cu–Co stage	Calcite	−2.2	−16.4	+13.9
FLC15D02B11-1	Cu–Co stage	Calcite	−2.4	−16.8	+13.5
FLC15D02B11-2	Cu–Co stage	Calcite	−2.3	−16.8	+13.5
FLC15D02B7-3	Cu–Co stage	Calcite	−3.1	−14.5	+15.9
FLC15D02B5	Cu–Co stage	Calcite	−3.1	−15.0	+15.4
FLC17D02B5	Cu–Co stage	Calcite	−2.0	−17.4	+13.0
FLC15D02B9	Cu–Co stage	Calcite	−2.5	−15.9	+14.4
FLC15D01B6-1	Cu–Co stage	Calcite	−3.9	−17.3	+13.0
FLC15D01B7	Cu–Co stage	Calcite	−3.8	−18.1	+12.2
FLC15D01B8-1	Cu–Co stage	Calcite	−2.8	−16.0	+14.4
LZP15D03B6-1	Pb–Zn stage	Calcite	−3.0	−14.5	+15.9
LZP15D03B6	Pb–Zn stage	Calcite	−3.1	−14.4	+16.0
LZP15D03B6-2	Pb–Zn stage	Calcite	−3.0	−14.4	+16.0
LZP15D03B7	Pb–Zn stage	Calcite	−3.3	−15.1	+15.3
LZP17D03B7	Pb–Zn stage	Calcite	−2.9	−14.6	+15.8
LZP15D01B6	Pb–Zn stage	Calcite	+1.7	−11.0	+19.5
LZP15D01B9	Pb–Zn stage	Calcite	−1.1	−9.7	+20.9
LZP17D01B9	Pb–Zn stage	Calcite	−1.6	−9.0	+21.6
LZP15D02B4-2	Pb–Zn stage	Calcite	+1.8	−8.6	+22.0
LZP15D03B1	Pb–Zn stage	Calcite	−2.3	−14.2	+16.2
LZP17D03B1	Pb–Zn stage	Calcite	−2.5	−16.0	+14.4
LZP15D02B4-1	Pb–Zn stage	Calcite	+1.7	−8.7	+21.9
LZP15D01B3	Pb–Zn stage	Calcite	−1.8	−11.1	+19.4
LZP15D02B6	Pb–Zn stage	Calcite	−0.2	−11.4	+19.1
LZP15D01B11	Pb–Zn stage	Calcite	−2.1	−9.8	+20.8
LZP17D01B11	Pb–Zn stage	Calcite	−2.2	−9.2	+21.4

The $\delta^{13}\text{C}_{\text{PDB}}$ values of calcite and ankerite from the Cu–Co ore are between -5.5% and -1.7% , and the $\delta^{18}\text{O}_{\text{SMOW}}$ values range from $+12.2\%$ to $+20.2\%$. The $\delta^{13}\text{C}_{\text{PDB}}$ values from Pb–Zn ore are between -3.3% and 1.8% , and the $\delta^{18}\text{O}_{\text{SMOW}}$ values range from $+14.4\%$ to $+22.0\%$.

4.3. S Isotopes

Nineteen samples of tetrahedrite and sphalerite were used to determine $\delta^{34}\text{S}$ values, and the results are listed in Table 2 and plotted in Figure 6. The $\delta^{34}\text{S}$ values range from $+5.2\%$ to $+9.5\%$. The majority of the minerals had $\delta^{34}\text{S}$ values peaking from $+7\%$ to $+9\%$. The $\delta^{34}\text{S}$ values of tetrahedrite range from $+5.2$ to $+9.5\%$, whereas those of sphalerite range from $+7.5\%$ to $+9\%$.

Table 2. $\delta^{34}\text{S}$ (‰) isotopic data from the Baiyangping Cu–Co–Pb–Zn deposit.

Samples	Stage	Mineral	$\delta^{34}\text{S}$ (V-CDT)‰
BYP15D02B6	Cu–Co stage	tetrahedrite	+9.2
BYP15D02B11-1	Cu–Co stage	tetrahedrite	+9.5
BYP15D02B13	Cu–Co stage	tetrahedrite	+8.1
BYP15D02B15	Cu–Co stage	tetrahedrite	+9.5
BYP15D02B17	Cu–Co stage	tetrahedrite	+9.3
BYP15D03B1	Cu–Co stage	tetrahedrite	+6.6

Table 2. Cont.

Samples	Stage	Mineral	$\delta^{34}\text{S}$ (V-CDT)‰
BYP15D03B10	Cu–Co stage	tetrahedrite	+7.9
BYP15D03B11	Cu–Co stage	tetrahedrite	+6.6
BYP15D03B12	Cu–Co stage	tetrahedrite	+7.0
BYP15D03B2	Cu–Co stage	tetrahedrite	+8.2
LZP15D02B13	Cu–Co stage	tetrahedrite	+5.2
LZP15D03B1	Cu–Co stage	tetrahedrite	+9.0
LZP15D03B6	Cu–Co stage	tetrahedrite	+6.9
FLC15D01B1-2	Pb–Zn stage	sphalerite	+7.2
FLC15D01B11	Pb–Zn stage	sphalerite	+9.0
FLC15D01B7	Pb–Zn stage	sphalerite	+8.2
FLC15D01B1-1	Pb–Zn stage	sphalerite	+7.5
FLC15D01B4	Pb–Zn stage	sphalerite	+7.8
FLC15D01B14	Pb–Zn stage	sphalerite	+8.1

Figure 6. Histogram of the sulfur isotope composition of each stage from the Baiyangping Cu–Co–Pb–Zn deposit.

5. Discussion

5.1. Ore-Forming Conditions

Fluid inclusions from the Cu–Co ores in quartz and carbonates of the Baiyangping deposit show homogenization temperatures of 146–233 °C, with the majority between 160 °C and 200 °C, and salinities of 2.7–24.8 wt % NaCl equiv (Figure 7). Fluid inclusions from the Pb–Zn ore indicate that the homogenization temperatures are between 137 °C and 175 °C, with a predominant temperature range between 120 °C and 160 °C. The salinities range from 5.9 to 22.8 wt % NaCl equiv. These data indicate that the mineralizing fluids are characterized by medium-low temperatures and relatively variable salinities [31,32]. However, the ore-forming fluid of the Cu–Co ore may have had a slightly higher temperature and similar salinities relative to the Pb–Zn ore (Figure 7). Previous research has shown that the deposition of Cu–Co–Pb–Zn minerals is affected by factors such as mineral liquefaction composition and co-existing minerals as well as by physical and chemical conditions [32–34].

Figure 7. Summary plot of homogenization temperatures, salinities, and pressure of fluid inclusions related to the two stages at the Baiyangping Cu–Co–Pb–Zn deposit.

5.2. Sources of Metals and Ore-Forming Fluids

The Baiyangping ore-bearing hydrothermal carbonates are characterized by $\delta^{18}\text{O}_{\text{SMOW}}$ values from +12.2‰ to +22.0‰ and the $\delta^{13}\text{C}_{\text{PDB}}$ variable from −5.5‰ to +1.8‰. In the diagram of $\delta^{18}\text{O}_{\text{SMOW}}$ versus $\delta^{13}\text{C}_{\text{PDB}}$, most of the hydrothermal carbonates from Pb–Zn and Cu–Co mineralizations are plotted within or near the fields of continental or marine carbonates. This feature indicates that the carbon of both Pb–Zn and Cu–Co mineralizing fluids may originate from the regional continental carbonates, which are similar to the regional Triassic carbonates [35–40]. Moreover, the $\delta^{18}\text{O}_{\text{SMOW}}$ of hydrothermal carbonates from the Pb–Zn and Cu–Co mineralizations show slight differences, with the latter showing lower $\delta^{18}\text{O}_{\text{SMOW}}$ values. During the relatively intense carbonate dissolution processes, namely water–rock interaction during the Cu–Co mineralizing phase, $\delta^{13}\text{C}_{\text{PDB}}$ remains unchanged while $\delta^{18}\text{O}_{\text{SMOW}}$ decreases. The $\delta^{18}\text{O}_{\text{SMOW}}-\delta^{13}\text{C}_{\text{PDB}}$ ranges of marine carbonate and continental carbonate come from Ohmoto, 1986 [41]. This may indicate that carbon sources may be driven by low- $\delta^{18}\text{O}_{\text{SMOW}}$ basinal brines or fluid input by meteoric water (Figure 8) [42–45]. Carbonates generally have C–O isotope compositions between mantle-sourced carbon and continental carbonates (Figure 8). The homogenization temperatures of fluid inclusions in hydrothermal ankerite and calcite from Baiyangping are relatively low. The variation in the carbon and oxygen isotopic compositions of the veined carbonates are similar to those of the regional Triassic limestone country rocks [43–46].

The $\delta^{34}\text{S}$ values of sulfides from the Baiyangping deposit range from +5.2‰ to +9.5‰. Samples of tetrahedrite from the Cu–Co ore have $\delta^{34}\text{S}$ values between +5.2‰ and +9.5‰, which resemble those of sphalerite from the Pb–Zn ore ranging from +7.5‰ to +9‰. Such features may provide evidence for both consistent and stable sulfur sources, as well as sulfate reduction processes during Cu–Co and Pb–Zn mineralization, which is consistent with previous interpretations [44,45].

Figure 8. Plots of calculated $\delta^{18}\text{O}_{\text{SMOW}}$ versus $\delta^{13}\text{C}_{\text{PDB}}$ from various samples of the Baiyangping Cu–Co–Pb–Zn deposit.

The sulfate reduction processes during sediment-hosted deposit mineralization are controlled by the geothermal gradients. Such processes may include thermal decomposition of sulfur-bearing matter at temperatures of $\sim 100\text{--}150\text{ }^{\circ}\text{C}$, thermochemical sulfate reduction in the presence of organic matter at $80\text{--}100\text{ }^{\circ}\text{C} < T < 160\text{--}180\text{ }^{\circ}\text{C}$, and bacterially mediated sulfate reduction at a temperature of $< 80\text{ }^{\circ}\text{C}$ [1,41]. The fluid temperatures during ore-forming hydrothermal activity are between $140\text{ }^{\circ}\text{C}$ and $200\text{ }^{\circ}\text{C}$, indicating that bacterially mediated sulfate reduction is unlikely to have taken place during Cu–Co and Pb–Zn mineralizations [45–49]. Thermochemical sulfate reduction may generate $0\text{--}15\%$ sulfur isotope fractionations during the transition from marine sulfate to H_2S within the temperature range of $80\text{ }^{\circ}\text{C} < T < 180\text{ }^{\circ}\text{C}$ [49]. Previous studies identified a large amount of organic matter and sulfates in the regional Triassic Sanhedong and Paleogene Yunlong formations [50–53], which are available for interaction between sulfates and organic reactants. The $\delta^{34}\text{S}$ sulfide values of $+5.2$ to $+9.5\%$ at the Baiyangping deposit also highlight the role of thermochemical sulfate reduction as a source of sulfur.

Thermal maturation of sulfur-bearing organic matter produces CH_4 along with H_2S , as a source of sulfur in sediment-hosted deposits [46]. The $\delta^{34}\text{S}$ values for the H_2S generated by such process are similar to the initial $\delta^{33}\text{S}$ value for sulfate, containing the relatively short time required for conversion from sulfate to sulfide [48]. However, the uniform $\delta^{34}\text{S}$ values of $+5.2\%$ to $+9.5\%$ from our samples are different from the initial $\delta^{34}\text{S}$ value for marine sulfate commonly ranging from $+15\%$ to $+25\%$, indicating that such mechanisms can be ruled out [50,51]. In summary, we propose that the Cu–Co and Pb–Zn mineralization-required sulfur at the Baiyangping deposit mainly originated from a reservoir characterized by thermochemical sulfate reduction.

5.3. Ore Genetic Processes and Comparison

It is proposed that the Cu–Co mineralization is contemporaneous with the Pb–Zn mineralization in the Baiyangping Cu–Co–Pb–Zn–Ag metallogenic district between ca. 33 Ma and 27 Ma [26,42], namely from the Oligocene to Miocene. This metallogenic event is temporarily associated with the deformation of the Lanping Basin that occurred during the India–Asia continental collision in the Palaeocene to Early Oligocene [54]. During the collisional event, the basin witnessed changes in tectonic setting and evolved into a foreland basin. It was during this period that the molasse conglomerate filled the basin

and formed the Eocene Baoxiangshi and Oligocene Jinsichang formations [53]. The last tectonic event in the Lanping Basin is represented by the transition from the foreland basin into the strike-slip and pull-apart basin during the Late Oligocene to Miocene [54]. Thus, the regional tectonic transition from transpression to transtension provided the tectonic setting for the formation of Cu–Co and Pb–Zn mineralizations during the Oligocene in the Baiyangping district [16,55].

Most Cu–Co–Pb–Zn orebodies at Baiyangping are associated with the NE-, NS-, and E-trending faults. The Pb–Zn mineralization is mainly hosted in Triassic–Jurassic carbonate rocks and Jurassic to Palaeocene clastic rocks, whereas the Cu–Co mineralization is hosted in Jurassic to Palaeocene clastic rocks. However, both the Pb–Zn and Cu–Co mineralizations exhibit homogeneous sulfur isotope compositions, indicating a uniform source of sulfur generated by thermochemical reduction of rocks in sedimentary strata. The mineralizing fluids sharply precipitated when encountering H₂S-rich fluids after thermochemical sulfate reduction. The Pb–Zn stage may occur in a process that the ore fluid might obtain metals from sedimentary strata [55–58]. Mineralizing hydrothermal fluids are derived from basinal brines, indicating the common metal sources and successive metallogenic sequences for Cu–Co and Pb–Zn mineralization. In summary, this study makes it clear that the Baiyangping deposit represents a counterpart to the sediment-hosted Cu–Co–Pb–Zn deposits in the Otavi Mountain Land of Namibia, in the Goodsprings district of Nevada, and in the Leeuwbosch and Thabazimbi district of Cornwall in South Africa [13,14].

6. Conclusions

The Oligocene–Miocene Baiyangping Pb–Zn–Cu–Co mineralization is characterized by carbonate–sulfide veins and mineralized dissolution-collapse breccias in fault zone cutting through carbonate and clastic rocks. Fluid inclusions from Cu–Co and Pb–Zn ores show that the ore-forming fluid originated from basinal brines. The C, O, and S isotope geochemistry suggests that the origin of the mineralization is sedimentary strata in the Lanping Basin. The mineralization controlling factors are principally thermochemical sulfate reduction, pH, and oxygen fugacity changes. We propose that the Baiyangping deposit is one of the rare examples of sediment host Cu–Co–Pb–Zn deposit related to the collision of the India and Asia continents.

Author Contributions: Conceptualization, J.Z.; methodology, J.Z., L.Y. and H.D.; software, J.Z., L.Y., J.Q. and Q.L.; validation, J.Z.; formal analysis, J.Z. and H.D.; investigation, L.Y., J.Z., K.S., Q.C., H.D., R.H. and L.L.; resources, H.D. and R.H.; data curation, J.Z. and H.D.; writing—original draft preparation, J.Z. and H.D.; writing—review and editing, J.Z. and H.D.; visualization, J.Z. and H.D.; supervision, J.Z.; project administration, J.Z.; and funding acquisition; H.D. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (Numbers 41872080), National Key Research and Development Project of China (Number 2020YFA0714802), and Most Special Fund from the State Key Laboratory of Geological Processes and Mineral Resources in China University of Geosciences (Beijing) of China (Number MSFGPMR201804).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets presented in this study can be obtained upon request to the corresponding author.

Acknowledgments: The authors thank the team members at CUGB for their field support, data analysis, constructive discussions, and comments.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Leach, D.L.; Sangster, D.F.; Kelley, K.D.; Large, R.R.; Garven, G.; Allen, C.; Gatzmer, J.; Wallters, S. Sediment-hosted lead–zinc deposit: A global perspective. *Econ. Geol.* **2005**, *100*, 561–607. [\[CrossRef\]](#)
2. Wang, C.M.; Deng, J.; Carranza, E.J.M.; Lai, X.R. Nature, diversity and temporal–spatial distributions of sediment-hosted Pb–Zn deposits in China. *Ore Geol. Rev.* **2014**, *56*, 327–351. [\[CrossRef\]](#)
3. Wang, C.M.; Rao, S.C.; Shi, K.X.; Bagas, L.; Chen, Q.; Zhu, J.X.; Duan, H.Y.; Liu, L.J. Rutile in amphibolite facies metamorphic rocks: A rare example from the East Qinling Orogen, China. *Appl. Sci.* **2021**, *11*, 8756. [\[CrossRef\]](#)
4. Wang, C.M.; Deng, J.; Bagas, L.; He, X.Y.; Zhang, J. Origin and classification of the Late Triassic Huaishuping gold deposit in the eastern part of the Qinling–Dabie Orogen, China: Implications for gold metallogeny. *Miner. Depos.* **2021**, *56*, 725–742. [\[CrossRef\]](#)
5. Liu, Y.F.; Qi, H.W.; Bi, X.W.; Hu, R.Z.; Qi, L.K.; Yin, R.S.; Tang, Y.Y. Mercury and sulfur isotopic composition of sulfides from sediment-hosted lead–zinc deposits in Lanping basin, Southwestern China. *Chem. Geol.* **2021**, *559*, 119910. [\[CrossRef\]](#)
6. Chen, Q.; Wang, C.M.; Du, B.; Shi, K.X.; Yang, L.F.; Zhu, J.X.; Duan, H.Y. Petrogenesis of the Late Triassic Biluoxueshan granitic pluton, SW China: Implications for the tectonic evolution of the Paleo–Tethys Sanjiang Orogen. *J. Asian Earth Sci.* **2021**, *211*, 104700. [\[CrossRef\]](#)
7. Du, B.; Wang, C.M.; Yang, L.F.; Shi, K.X.; Chen, Q.; Zhu, J.X. Petrogenesis of the Cenozoic Lianhuashan pluton: Constrained by zircon U–Pb geochronology, Lu–Hf isotope and geochemistry. *Geol. J.* **2020**, *55*, 3377–3400. [\[CrossRef\]](#)
8. Wang, C.M.; Bagas, L.; Chen, J.Y.; Yang, L.F.; Zhang, D.; Du, B.; Shi, K.X. The genesis of the Liancheng Cu–Mo deposit in the Lanping Basin of SW China: Constraints from geology, fluid inclusions, and Cu–S–H–O isotopes. *Ore Geol. Rev.* **2018**, *92*, 113–128. [\[CrossRef\]](#)
9. Wang, C.M.; Yang, L.F.; Bagas, L.; Noreen, E.; Chen, J.Y.; Du, B. Mineralization processes at the giant Jinding Zn–Pb deposit, Lanping Basin, Sanjiang Tethys Orogen: Evidence from in-situ trace element analysis of pyrite and marcasite. *Geol. J.* **2018**, *53*, 1279–1294. [\[CrossRef\]](#)
10. Zou, Z.C.; Hu, R.Z.; Bi, X.W.; Wu, L.Y.; Feng, C.X.; Tang, Y.Y. Noble gas and stable isotopic constraints on the origin of the Ag–Cu polymetallic ore deposits in the Baiyangping area, Yunnan Province, SW China. *Resour. Geol.* **2016**, *66*, 183–198. [\[CrossRef\]](#)
11. Pirajno, F.; Joubert, B.D. An overview of carbonate-hosted mineral deposits in the Otavi Mountain Land, Namibia: Implications for ore genesis. *J. Afr. Earth Sci.* **1993**, *16*, 265–272. [\[CrossRef\]](#)
12. Shelton, K.L.; Burstein, I.B.; Hagni, R.D.; Vierrether, C.B.; Grant, S.K.; Hennigh, Q.T.; Bradley, M.F.; Brandom, R.T. Sulfur isotope evidence for penetration of MVT fluids into igneous basement rocks, southeast Missouri, USA. *Miner. Depos.* **1995**, *30*, 339–350. [\[CrossRef\]](#)
13. Vikre, P.; Browne, Q.J.; Fleck, R.; Hofstra, A.; Wooden, J. Ages and sources of components of Zn–Pb, Cu, precious metal, and platinum group element deposits in the Goodsprings District, Clark County, Nevada. *Econ. Geol.* **2011**, *106*, 381–412. [\[CrossRef\]](#)
14. Möller, V.; Klemka, R.; Joachimski, M.; Barton Jr, J.M. Hydrothermal controls on iron and lead mineralization on the farms Leeuwbosch and Cornwall, Thabazimbi district, South Africa. *Ore Geol. Rev.* **2014**, *63*, 40–63. [\[CrossRef\]](#)
15. He, L.Q.; Song, Y.C.; Chen, K.X.; Hou, Z.Q.; Yu, F.M.; Yang, Z.S.; Wei, J.Q.; Li, Z.; Liu, Y.C. Thrust-controlled, sediment-hosted, Himalayan Zn–Pb–Cu–Ag deposits in the Lanping foreland fold belt, eastern margin of Tibetan Plateau. *Ore Geol. Rev.* **2009**, *36*, 106–132. [\[CrossRef\]](#)
16. Deng, J.; Wang, Q.F.; Li, G.J.; Li, C.S.; Wang, C.M. Tethys tectonic evolution and its bearing on the distribution of important mineral deposits in the Sanjiang region, SW China. *Gondwana Res.* **2014**, *26*, 419–437. [\[CrossRef\]](#)
17. Wang, C.M.; Bagas, L.; Lu, Y.J.; Santosh, M.; Du, B.; McCuaig, T.C. Terrane boundary and spatio-temporal distribution of ore deposits in the Sanjiang Tethyan Orogen: Insights from zircon Hf–isotopic mapping. *Earth-Sci. Rev.* **2016**, *156*, 39–65. [\[CrossRef\]](#)
18. Wang, C.M.; Deng, J.; Bagas, L.; Wang, Q.F. Zircon Hf–isotopic mapping for understanding crustal architecture and metallogenesis in the Eastern Qinling Orogen. *Gondwana Res.* **2017**, *50*, 293–310. [\[CrossRef\]](#)
19. He, L.Q.; Chen, K.X.; Wei, J.Q.; Yu, F.M. Geological and geochemical characteristics and genesis of ore deposits in eastern ore belt of Baiyangping area, Yunnan Province. *Min. Depos.* **2005**, *24*, 61–70. (In Chinese with English Abstract)
20. Hou, Z.Q.; Song, Y.C.; Li, Z.; Wang, Z.L.; Yang, Z.M.; Yang, Z.S.; Liu, Y.C.; Tian, S.H.; He, L.Q.; Chen, K.X.; et al. Thrust-controlled, sediments-hosted Pb–Zn–Ag–Cu deposits in eastern and northern margins of Tibetan orogenic belt: Geological features and tectonic model. *Miner. Depos.* **2008**, *27*, 123–144. (In Chinese with English Abstract)
21. Li, X.M.; Song, Y.G. Cenozoic evolution of tectono–fluid and metallogenic process in the Lanping Basin, western Yunnan Province, Southwest China: Constraints from apatite fission track data. *Chin. J. Geochem.* **2006**, *15*, 405–408. [\[CrossRef\]](#)
22. Xue, C.J.; Chen, Y.C.; Wang, D.H.; Yang, J.M.; Yang, W.G. Geology and isotopic composition of helium, neon, xenon and metallogenic age of the Jinding and Baiyangping ore deposits, northwest Yunnan. *Sci. China Ser. D-Earth Sci.* **2006**, *46*, 789–800. [\[CrossRef\]](#)
23. Xue, C.J.; Zeng, R.; Liu, S.W.; Chi, G.X.; Qing, H.R.; Chen, Y.C.; Yang, J.M.; Wang, D.H. Geologic, fluid inclusion and isotopic characteristics of the Jinding Zn–Pb deposit, western Yunnan, South China: A review. *Ore Geol. Rev.* **2007**, *31*, 337–359. [\[CrossRef\]](#)
24. Liu, Y.F.; Qi, H.W.; Bi, X.W.; Hu, R.Z.; Qi, L.K.; Yin, R.S.; Tang, Y.Y. Two types of sediment-hosted Pb–Zn deposits in the northern margin of Lanping basin, SW China: Evidence from sphalerite trace elements, carbonate C–O isotopes and molybdenite Re–Os age. *Ore Geol. Rev.* **2021**, *131*, 104016. [\[CrossRef\]](#)
25. Bodnar, R.J. Revised equation and table for determining the freezing point depression of H₂O–NaCl solutions. *Geochim. Cosmochim. Acta* **1993**, *57*, 683–684. [\[CrossRef\]](#)

26. Zou, Z.C.; Hu, R.Z.; Bi, X.W.; Wu, L.Y.; Zhang, J.R.; Tang, Y.Y.; Li, N. Absolute and relative dating of Cu and Pb–Zn mineralization in the Baiyangping area, Yunnan Province, SW China: Sm–Nd geochronology of calcite. *Geochemistry* **2015**, *49*, 103–112. [\[CrossRef\]](#)
27. Feng, C.X.; Bi, X.W.; Liu, S.; Hu, R.Z. Fluid inclusion, rare earth element geochemistry, and isotopic characteristics of the eastern ore zone of the Baiyangping polymetallic ore district, northwestern Yunnan Province, China. *J. Asian Earth Sci.* **2014**, *85*, 140–153. [\[CrossRef\]](#)
28. Yang, L.F.; Wang, C.M.; Bagas, L.; Du, B.; Zhang, D. Mesozoic–Cenozoic sedimentary rock records and applications for provenance of sediments and affiliation of the Simao Terrane, SW China. *Int. Geol. Rev.* **2019**, *61*, 2291–2312. [\[CrossRef\]](#)
29. Lecumberri–Sanchez, P.; Steele–MacInnis, M.; Bodnar, R.J. A numerical model to estimate trapping conditions of fluid inclusions that homogenize by halite disappearance. *Geochim. Cosmochim. Acta* **2012**, *92*, 14–22. [\[CrossRef\]](#)
30. Roedder, E. Fluid inclusions. *Miner. Soc. Am.* **1984**, *12*, 71–77. [\[CrossRef\]](#)
31. Bauer, M.E.; Burisch, M.; Ostendorf, J.; Krause, J.; Frenzel, M.; Seifert, T.; Gutzmer, J. Trace element geochemistry of sphalerite in contrasting hydrothermal fluid systems of the Freiberg district, Germany: Insights from LA-ICP-MS analysis, nearinfrared light microthermometry of sphalerite-hosted fluid inclusions, and sulfur isotope geochemistry. *Miner. Depos.* **2019**, *54*, 237–262.
32. Bauer, M.E.; Seifert, T.; Burisch, M.; Krause, J.; Richter, N.; Gutzmer, J. Indiumbearing sulfides from the Hämmerlein skarn deposit, Erzgebirge, Germany: Evidence for late-stage diffusion of indium into sphalerite. *Miner. Depos.* **2019**, *54*, 175–192. [\[CrossRef\]](#)
33. González, L.A.; Lohmann, K.C. Carbon and oxygen isotopic composition of Holocene reefal carbonates. *Geology* **1985**, *13*, 811–814. [\[CrossRef\]](#)
34. Feng, C.X.; Liu, S.; Bi, X.W.; Hu, R.Z.; Chi, G.X.; Chen, J.J.; Feng, Q.; Guo, X.L. An investigation of metallogenic chronology of eastern ore block of the Baiyangping Pb–Zn–Cu–Ag ore deposit, Lanping Basin, western Yunnan Province. *Miner. Depos.* **2017**, *33*, 691–704. (In Chinese with English Abstract)
35. Anderson, G.M. The hydrothermal transport and deposition of galena and sphalerite near 100 °C. *Econ. Geol.* **1973**, *68*, 480–492. [\[CrossRef\]](#)
36. Markl, G.; Lahaye, Y.; Schwinn, G. Copper isotopes as monitors of redox processes in hydrothermal mineralization. *Geochim. Cosmochim. Acta* **2006**, *70*, 4215–4228. [\[CrossRef\]](#)
37. Tagirov, B.R.; Suleimenov, O.M.; Seward, T.M. Zinc complexation in aqueous sulfide solutions: Determination of the stoichiometry and stability of complexes via ZnS [Cr] solubility measurements at 100 °C and 150 bars. *Geochim. Cosmochim. Acta* **2007**, *71*, 4942–4953. [\[CrossRef\]](#)
38. Sverjensky, D.A. Genesis of Mississippi Valley–type lead–zinc deposits. *Ann. Rev. Earth Planet. Sci.* **1986**, *14*, 177–199. [\[CrossRef\]](#)
39. Albarède, F. The stable isotope geochemistry of copper and zinc. *Rev. Mineral. Geochem.* **2004**, *55*, 409–427. [\[CrossRef\]](#)
40. Gagnevin, D.; Boyce, A.J.; Barrie, C.D.; Menuge, J.F.; Blakeman, R.J. Zn, Fe and S isotope fractionation in a large hydrothermal system. *Geochim. Cosmochim. Acta* **2012**, *88*, 183–198. [\[CrossRef\]](#)
41. Asael, D.; Matthews, A.; Bar–Matthews, M.; Halicz, L.; Ehrlich, S.; Teplyakov, N. Redox fractionation of copper isotopes in sedimentary conditions. *Geochim. Cosmochim. Acta* **2017**, *69*, A216. [\[CrossRef\]](#)
42. Driesner, T.; Heinrich, C.A. The system H₂O–NaCl. Part I: Correlation formulae for phase relations in temperature–pressure–composition space from 0 to 1000 °C, 0 to 5000 bar, and 0 to 1 X_{NaCl}. *Geochim. Cosmochim. Acta* **2007**, *71*, 4880–4901. [\[CrossRef\]](#)
43. Wang, C.M.; Zhang, D.; Wu, G.G.; Santosh, M.; Zhang, J.; Xu, Y.G.; Zhang, Y.Y. Geological and isotopic evidence for a magmatic–hydrothermal origin of the Ag–Pb–Zn deposits in the Lengshuikeng district, east–central China. *Miner. Depos.* **2014**, *49*, 733–749. [\[CrossRef\]](#)
44. Wang, C.M.; Deng, J.; Santosh, M.; Lu, Y.J.; McCuaig, T.C.; Carranza, E.J.M.; Wang, Q.F. Age and origin of the Bulangshan and Mengsong granitoids and their significance for post–collisional tectonics in the Changning–Menglian Paleo–Tethys Orogen. *J. Asian Earth Sci.* **2015**, *113*, 656–676. [\[CrossRef\]](#)
45. Ohmoto, H.; Rye, R. Isotopes of sulfur and carbon. In *Geochemistry of Hydrothermal Ore Deposits*, 1st ed.; Barnes, H.L., Ed.; John Wiley: New York, NY, USA, 1979; pp. 509–576.
46. Zhang, J.R.; Wen, H.J.; Qiu, Y.Z.; Zhou, Z.C.; Du, S.J.; Wu, S.Y. Spatial–temporal evolution of ore–forming fluids and related mineralization in the western Lanping basin, Yunnan Province, China. *Ore Geol. Rev.* **2015**, *60*, 90–108. [\[CrossRef\]](#)
47. Ohmoto, H. Stable isotope geochemistry of ore deposits. In *Stable Isotopes in High Temperature Geological Processes: Reviews in Mineralogy and Geochemistry* 16; Valley, J.W., Taylor, H.P., O'Neill, J.R., Eds.; Mineralogical Society of America: Washington, DC, USA, 1986; pp. 491–599.
48. Zhang, J.R.; Wen, H.J.; Qiu, Y.Z.; Zhang, Y.X.; Li, C. Ages of sediment–hosted Himalayan Pb–Zn–Cu–Ag polymetallic deposits in the Lanping basin, China: Re–Os geochronology of molybdenite and Sm–Nd dating of calcite. *J. Asian Earth Sci.* **2013**, *73*, 284–295. [\[CrossRef\]](#)
49. Xue, W.; Xue, C.J.; Li, H.J.; Chi, G.X.; Zeng, R. Sources of the ore–forming Material of the Baiyangping poly–metallic deposit in Lanping Basin, northwestern Yunnan: Constraints from C, H, O, S and Pb isotope geochemistry. *Geoscience* **2012**, *26*, 663–672. (In Chinese with English Abstract)
50. Machel, H.G. Bacterial and thermochemical sulfate reduction in diagenetic settings: Old and new insights. *Sediment. Geol.* **2001**, *140*, 143–175. [\[CrossRef\]](#)
51. Kashefi, K.; Lovley, D.R. Extending the upper temperature limit for life. *Science* **2003**, *301*, 934. [\[CrossRef\]](#)

52. Peevler, J.; Fayek, M.; Misra, K.C.; Riciputi, L.R. Sulfur isotope microanalysis of sphalerite by SIMS: Constraints on the genesis of Mississippi valley-type mineralization, from the Mascot-Jefferson City district, East Tennessee. *J. Geochem. Explor.* **2003**, *80*, 277–296. [[CrossRef](#)]
53. Gao, Y.B.; Xue, C.J.; Zeng, R. Forming mechanisms of H₂S in the Jinding Pb–Zn deposit, Lanping Basin, Northwest Yunnan Province. *J. Earth Sci. Environ.* **2008**, *30*, 367–372. (In Chinese with English Abstract)
54. Chen, Q.; Wang, C.M.; Leon, B.; Zhang, Z.C.; Du, B. Time scales of multistage magmatic-hydrothermal mineralization at the giant Yulong porphyry Cu–Mo deposit in eastern Tibet: Insights from titanium diffusion in quartz. *Ore Geol. Rev.* **2021**, *139*, 104459. [[CrossRef](#)]
55. Dupont–Nivet, G.; Lippert, P.C.; van Hinsbergen, D.J.; Meijers, M.J.; Kapp, P. Palaeolatitude and age of the Indo–Asia collision: Palaeomagnetic constraints. *Geophys. J. Int.* **2010**, *182*, 1189–1198. [[CrossRef](#)]
56. Tao, X.F.; Zhu, L.D.; Liu, D.Z.; Wang, G.Z.; Li, Y.G. The Formation and evolution of the Lanping basin in Western Yunnan. *J. Chengdu Univ. Technol.* **2002**, *29*, 521–525. (In Chinese with English Abstract)
57. Wang, C.M.; Deng, J.; Zhang, S.T.; Xue, C.J.; Yang, L.Q.; Wang, Q.F.; Sun, X. Sediment-hosted Pb–Zn deposits in Southwest Sanjiang Tethys and Kangdian area on the western margin of Yangtze Craton. *Acta Geol. Sin-Engl.* **2010**, *84*, 1428–1438. [[CrossRef](#)]
58. Tang, Y.Y.; Yin, R.S.; Hu, R.Z.; Sun, G.Y.; Zou, Z.C.; Zhou, T.; Bi, X. Mercury isotope constraints on the sources of metals in the Baiyangping Ag–Cu–Pb–Zn polymetallic deposits, SW China. *Miner. Depos.* **2021**, *468*. [[CrossRef](#)]