

Article

Sr-Nd-Hf Isotopic Characteristics of Ore-Bearing Intrusive Rocks in the Chating Cu-Au Deposit and Magushan Cu-Mo Deposit of Nanling-Xuancheng Ore Concentration Area and Their Geological Significance

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Abstract

The Chating Cu-Au and Magushan Cu-Mo deposits in Anhui province are two representative deposits within the recently defined Nanling-Xuancheng ore concentration area in the Middle and Lower Yangtze River Metallogenic Belt (MLYB). Magmatism and mineralization for the area are not well known at present due to a lack of in-depth studies on the petrogenesis of ore-bearing intrusive rocks and their relationship with deposits. Here, the ore-bearing intrusive rocks of the two deposits are investigated through analyses of whole-rock geochemistry and Sr-Nd isotopes, zircon U-Pb ages, and zircon Hf isotopes. The results reflect the two intrusions, both formed in the Early Cretaceous (138.9 ± 0.8 Ma and 132.2 ± 1.3 Ma). They belong to the sub-alkaline high-K calc-alkaline series, while trace elements are enriched in LILEs and LREE and depleted in HFSEs. However, the intrusions of the Chating deposit ($I_{\text{Sr}} = 0.7064\text{--}0.7068$; $\varepsilon_{\text{Nd}}(t) = -8.5\text{--}-7.3$; $\varepsilon_{\text{Hf}}(t) = -11.9\text{--}-7.0$) have obviously different Sr-Nd-Hf isotopic compositions from the intrusions of the Magushan deposit ($I_{\text{Sr}} = 0.7079\text{--}0.7081$; $\varepsilon_{\text{Nd}}(t) = -5.7\text{--}-5.4$; $\varepsilon_{\text{Hf}}(t) = -5.4\text{--}-3.6$). The characteristics indicate that the two intrusions were formed in the same diagenetic ages and tectonic settings and derived from a crust–mantle mixture with predominant mantle-derived materials. But the crust materials of sources are different, which further leads to different metallogenic elements, showing that the Chating deposit is enriched in Cu and Au, while the Magushan deposit is enriched in Mo. Moreover, the characteristics and magma sources of two intrusions and metallogenic elements correspond respectively to the Tongling Cu-Au polymetallic ore concentration area in the MLYB and the southern Anhui Mo polymetallic ore concentration area in the Jiangnan orogen. The correlation implies differences in magmatism and mineralization between the northwestern and southeastern parts of the Nanling-Xuancheng ore concentration area, demarcated by the Jiangnan Deep Fault. These variations were mainly controlled by the Pre-Sinian crustal basement.



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Keywords: ore-bearing intrusive rocks; Sr-Nd-Hf isotopes; Chating Cu-Au deposit; Magushan Cu-Mo deposit; Nanling-Xuancheng ore concentration area

1. Introduction

The Nanling-Xuancheng ore concentration area (NXOR) in Anhui Province has recently revealed a series of Cu-Au polymetallic deposits, including the Chating Cu-Au deposit, Magushan Cu-Mo deposit, Tongshan-Qiaomaishan Cu-S deposit, and Changshan Pb-Zn deposit, demonstrating significant prospecting potential. Geological surveys and studies indicate that mineralization in the NXOR is closely associated with the Early Cretaceous magmatism and related hydrothermal activities, primarily classified as porphyry-skarn deposits [1–5]. However, these deposits exhibit various metallogenic characteristics and temporal–spatial distributions demarcated by the Jiangnan Deep Fault, which remain systematically investigated. Furthermore, as a newly delineated ore concentration area within the Middle and Lower Yangtze River Metallogenic Belt (MLYB) [6], the regional magmatism and mineralization of the NXOR also require further study. This study focuses on the ore-bearing intrusive rocks from the Chating Cu-Au and Magushan Cu-Mo deposits, which represent distinct metallogenic element assemblages on either side of the Jiangnan Deep Fault. Comprehensive analyses of whole-rock major and trace elements, Sr-Nd isotopes, zircon U-Pb dating, and Hf isotopes were conducted to constrain magma sources and their metallogenic implications. The results provide critical insights into the Mesozoic magmatic-mineralization processes within the NXOR.

2. Geological Setting

The Nanling-Xuancheng ore concentration area (NXOR) is located to the southeast of the Middle and Lower Yangtze River Metallogenic Belt (MLYB), with the Nanling-Xuancheng Basin constituting its core structure and surface predominantly covered by Quaternary sediments (Figure 1). The NXOR is confined by deep faults. It is bounded to the east by the NE-striking Nandu-Jintan Fault, which is adjacent to the Liyang volcanic basin. To the west is the Qingshuihe-Hewan Fault, which is connected to the Tongling Cu-Au polymetallic ore concentration area and the Fanchang-Ningwu volcanic basin. To the north is the concealed NW-trending Chaohu-Wuhu Fault, which links with the Lishui volcanic basin, and to the south is the E–W-oriented Zhouwang Fault, which is adjacent to the South Anhui metallogenic belt. The Zhouwang Fault represents the central segment of the NE-striking Yangxin-Changzhou fault (southern boundary of the MLYB). Moreover, the NXOR is cut by the NE-trending Jiangnan Deep Fault in its central domain. The Jiangnan Deep Fault constitutes a giant concealed paleo-fault zone traversing West Guangxi, Southeast Guizhou, Northwest Hunan, Southeast Hubei, Northwest Jiangxi, Southeast Anhui, and Southern Jiangsu [6]. The syndepositional fault has been active since its formation in the Cambrian, serving as the boundary between the Lower Yangtze and Jiangnan terranes [6,7].

The strata of the Nanling-Xuancheng ore concentration area (NXOR) comprises upper and lower structural layers, corresponding to the caprock and basement, respectively. The basement consists of Silurian to Early Triassic strata, with Silurian–Devonian strata dominated by shallow-marine to littoral clastic rocks, while Carboniferous to Lower Triassic strata are primarily carbonate rocks. The caprock comprises Cretaceous to Quaternary strata characterized by continental volcanic rocks and intracontinental depression red bed formations (primarily sandstone, conglomerate, and mudstone). The basement is superimposed by multiple NE thrust-nappe tectonics, which is from west to east: the Xinhezhuang-Liqiao nappe, the Jingtingshan nappe, and the Magushan nappe [6,8–10]. The thrust-nappe tectonics, composed of basement strata, covers the Lower Cretaceous volcanic rocks, with inferred limited movement distance based on regional stratigraphic distribution characteristics. The thrust-nappe structures concurrently manifest as anticlinorium, featuring NE complex folds/overtaken folds with SE-dipping axial planes, accompanied by imbricate thrust-detachment faults of the same strike and dip, and NW-striking near-vertical lateral faults.

Geophysical investigations reveal consistent tight folding and imbricate thrust-detachment fault systems between the basement and superimposed nappe/anticlinorium [10]. The NXOR Mesozoic intrusions and associated Cu-Au polymetallic deposits predominantly occur in the basement and superimposed nappe structures, and deposits with genetic links to volcanic rocks on the caprock have not been discovered (Figure 1).

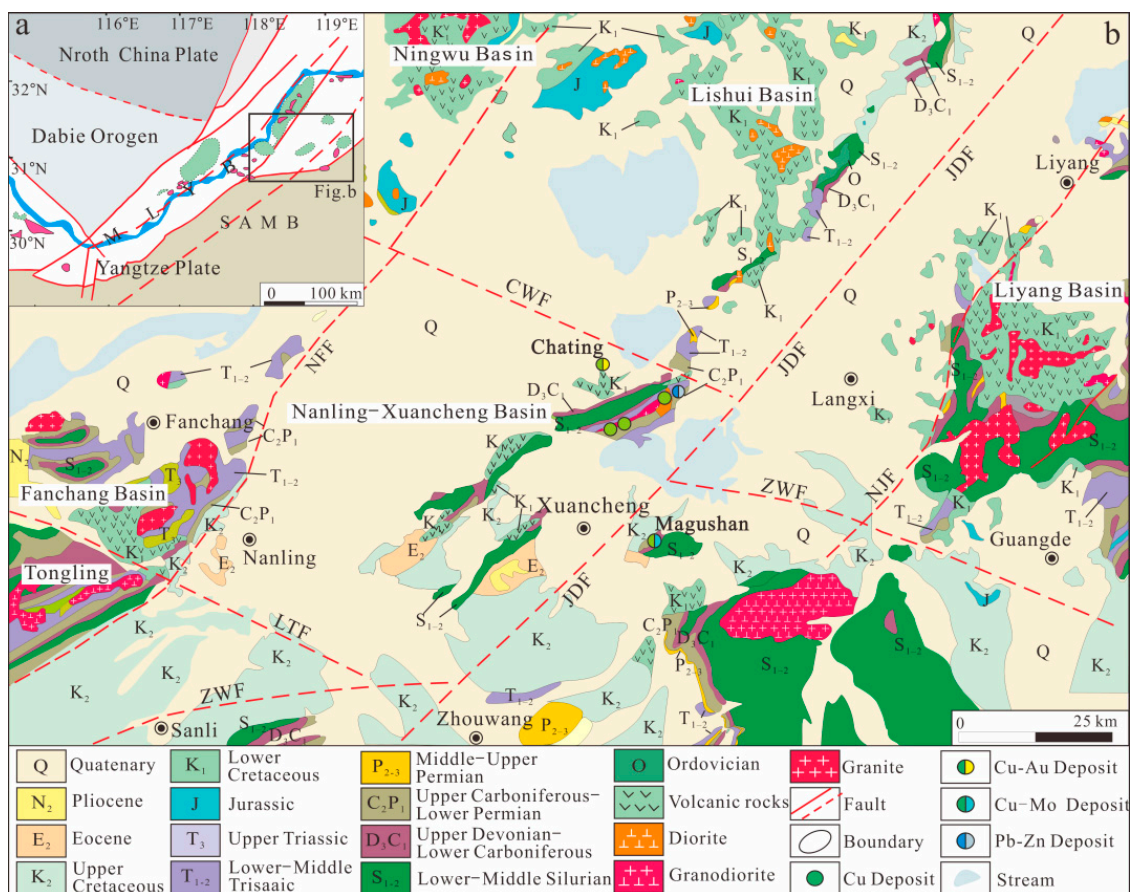


Figure 1. (a) Sketch regional geological map of MLYB; (b) Regional geological map of the Nanling-Xuancheng ore concentration area (modified from [6]). MLYB: the Middle-Lower Yangtze River metallogenic belt; SAMB: Southern Anhui metallogenic belt; CWF: Chaohu-Wuhu fault; NFF: Nanling-Fangshan fault; LTF: Lujiang-Tongling fault; ZWF: Zhouwang Fault; JDF: Jiangnan Deep Fault.

3. Geology of the Ore Deposits and Description of Samples

The Chating porphyry Cu-Au deposit is located 20 km north of Xuancheng City [4,5,11]. The deposit occurs in the Nanling-Xuancheng basin basement on the north-western side of the NE-striking Jiangnan Deep Fault. The main bodies of the deposit are concentrated in the cryptoexplosive breccia pipe and occur as irregular lenses [2,4,5]. The deposit contains proven reserves of 0.65 Mt Cu at 0.54 wt.% average grade, with associated Au of 248.15 t and 0.43 g/t average grade. The ore-bearing quartz diorite porphyry has an irregular NE-trending lenticular apophysis (>4000 m length, <500 m width) with near-vertical (Figure 2a,b). The samples were obtained from drilling cores. The rocks are often cut by dikes of diorite porphyry and lamprophyre and change locally into granodiorite porphyry (Figure 2a,b). The quartz diorite porphyry are often grayish-white to grayish-black and show porphyritic texture and massive structure (Figure 3a,b). The phenocrysts (30%–80%) comprise 50%–60% plagioclase, 20%–30% amphibole, 5%–10% quartz, and 3%–5% biotite. The matrixes comprise fine-grained plagioclase, quartz, K-feldspar, amphibole, and biotite. The rocks experienced carbonatization, chloritization, and sericitization.

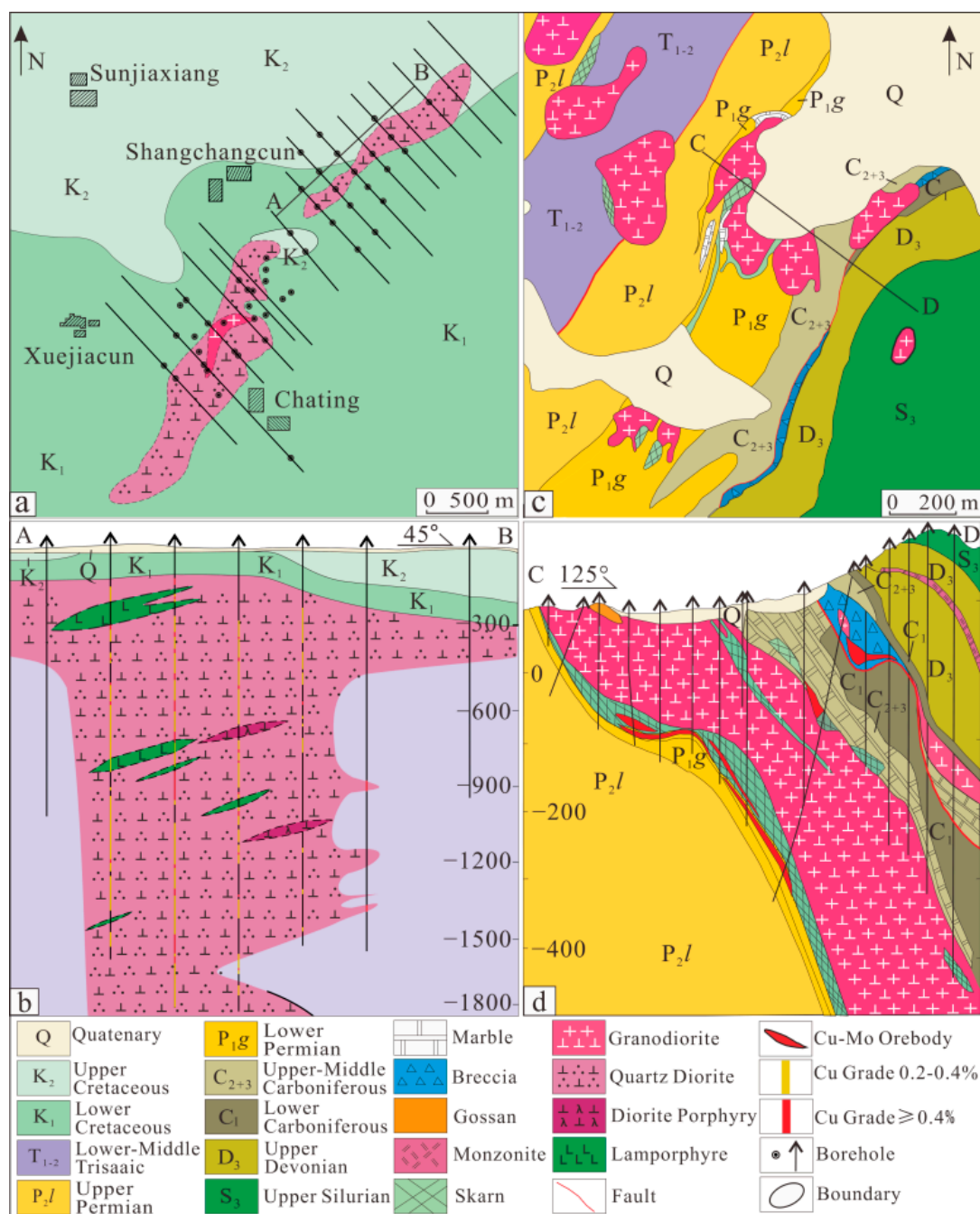


Figure 2. Geological maps of the plane and the prospecting profile (modified from [1,2]): (a,b) Chating Cu-Au deposit; (c,d) Magushan Cu-Mo deposit.

The Magushan skarn Cu-Mo deposit is located 15 km east of Xuancheng City. The deposit occurs on the northwestern side of the Magushan overturned anticline, which controls the location and shape of the ore bodies. The ore bodies, occurring in the contact zones between the ore-bearing intrusive rocks and Carboniferous limestones, are irregular lenticular shapes (Figure 2c,d), with Cu grades up to 10.44 wt.% (industrial grade 0.6–1.2 wt.%) and Mo grades up to 1.27 wt.% (industrial grade 0.06–0.12 wt.%) of Mo [1]. The ore-bearing granodiorite porphyry, occurring as irregular NE-trending lenticular apophysis, intrudes into the interface between the Permian Qixia Formation and the Carboniferous Gaolishan Formation and the interlayers of the Carboniferous–Permian Huanglong-Chuanshan Formation. The samples were obtained from outcrops. The granodiorite porphyries are often flesh-red and show porphyritic texture and massive structure (Figure 3c,d). The

phenocrysts (40%–60%) comprise 40%–55% plagioclase, 15%–25% quartz, 10%–20% K-feldspar, 5%–10% amphibole, and 3%–6% biotite. The matrixes comprise fine-grained quartz, plagioclase, K-feldspar, and biotite. The rocks primarily experienced chloritization and potash feldspathization.

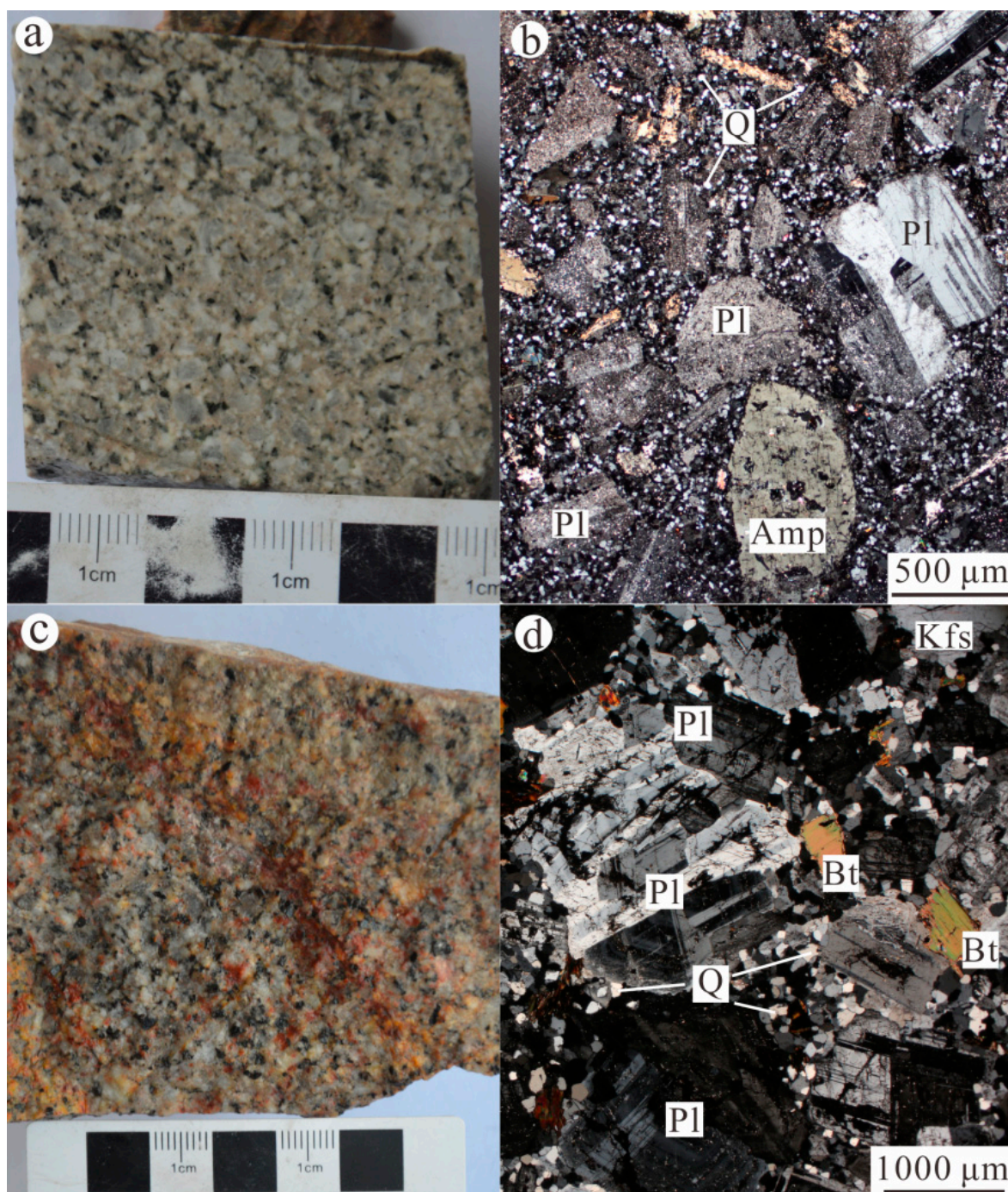


Figure 3. Photographs of the hand specimen and micropetrography of the ore-bearing intrusive rocks. (a,b) The ore-bearing quartz diorite porphyry of the Chating Cu-Au deposit; (c,d) The ore-bearing granodiorite porphyry of the Magushan Cu-Mo deposit. Kfs—K feldspar; Bt—biotite; Amp—amphibole; Q—quartz; Pl—plagioclase.

4. Analytical Methods

Based on detailed investigation of geological characteristics, ore-bearing intrusion distribution, and rock occurrence, ore-bearing quartz diorite porphyry of the Chating

Cu-Au deposit was obtained from drill cores, and ore-bearing granodiorite porphyry of the Magushan Cu-Mo deposit was obtained from outcrops.

Whole-rock major and trace elements of the samples were analyzed at the Guangzhou Aoshi Mineral Laboratory. Major element contents were analyzed using X-ray fluorescence (XRF). The instruments used were an Agilent 5110 from Agilent Technologies, Inc., Santa Clara, CA, USA inductively coupled plasma emission spectrometer and a PANalytical PW2424 X-ray fluorescence spectrometer. The analysis error for major elements is within 10%. Trace element analysis was performed using inductively coupled plasma mass spectrometry (ICP-MS, M61-MS81). The instruments used for this purpose were an Agilent 5110 inductively coupled plasma emission spectrometer and an Agilent 7900 ICP-MS, with a relative error for trace elements of less than 5%. Methodology follows established protocols [12].

Whole-rock Sr-Nd isotopic analyses were conducted at the Key Laboratory of Crust-Mantle Materials and Environments, University of Science and Technology of China. Isotopic data were obtained using a Finnigan MAT-262 mass spectrometer, and Sr and Nd isotopic ratios were corrected for mass fractionation relative to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively. More details on analytical procedures are given in [13].

Zircon single mineral separation and target preparation were conducted at Nanjing Hongchuang Geological Exploration Technology Service Co., Ltd., Nanjing, China. Zircon U-Pb dating and Lu-Hf isotope analyses were conducted at Hefei University of Technology, Hefei, China. U-Pb dating was performed using an Agilent 7900 Quadrupole ICP-MS instrument coupled to a Photon Machines Analyte HE 193 nm ARF excimer laser-ablation (LA) system. Each analysis was performed using a uniform spot diameter of 32 μm at 7 Hz with an energy of ~ 80 mJ for 60 s, following a 20 s gas blank measurement. Standard materials, including 91500, SRM610, and Plesovice zircon, were used as external standards. The zircon isotope ratios were calculated using the ICP-MS DataCal 12.2 software [14]. Lu-Hf isotopes were used in a Thermo Neptune MC-ICP MS in combination with a Teledyne Photon Machine Analyte HE excimer ARF laser ablation system. Each analysis was performed using a uniform spot diameter of 40 μm at 8 Hz with an energy of ~ 3.0 J/cm² for 30 s, following the analytical method described by [15].

5. Results

5.1. Whole-Rock Geochemistry

Whole-rock major and trace elements for ore-bearing quartz diorite porphyry (QDP) of the Chating Cu-Au deposit and ore-bearing granodiorite porphyry (GP) of the Magushan Cu-Mo deposit are listed in Supplementary Table S1. The QDP and GP have similar major element compositions, with SiO₂ ranging from 58.35 to 61.47 wt.% and 63.12 to 65.39 wt.%, K₂O from 2.66 to 4.06 wt.% and 2.56 to 3.25 wt.%, and Na₂O + K₂O from 7.32 to 8.55 wt.% and 5.24 to 6.45 wt.%, respectively. On the TAS (Na₂O + K₂O vs. SiO₂, Figure 4a) and SiO₂ versus K₂O diagrams (Figure 4b), the QDP and GP mostly plot in the fields of sub-alkaline high-K calc-alkaline series rocks. In the primitive-mantle-normalized incompatible trace element spidergrams (Figure 4c), both intrusive rocks show similar patterns with enrichment in the large ion lithophile elements (LILEs, e.g., Rb, Ba, K, and Sr) and depletion in the high field-strength element (HFSEs, e.g., Nb, Ta, and Ti). They display similar patterns in the chondrite-normalized REE diagrams (Figure 4d), so that $\Sigma\text{REE} = 99.9\text{--}158.2 \times 10^{-6}$ g/g, LREE/HREE = 6.86–13.25, La_N/Yb_N = 6.63–14.98, and $\delta\text{Eu} = 0.81\text{--}1.10$. However, the whole-rock geochemistry analysis results (Figure 4) show the QDP and GP are similar to the Tongling ore concentration area in the MLYB and the southern Anhui ore concentration area in the Jiangnan orogen, respectively.

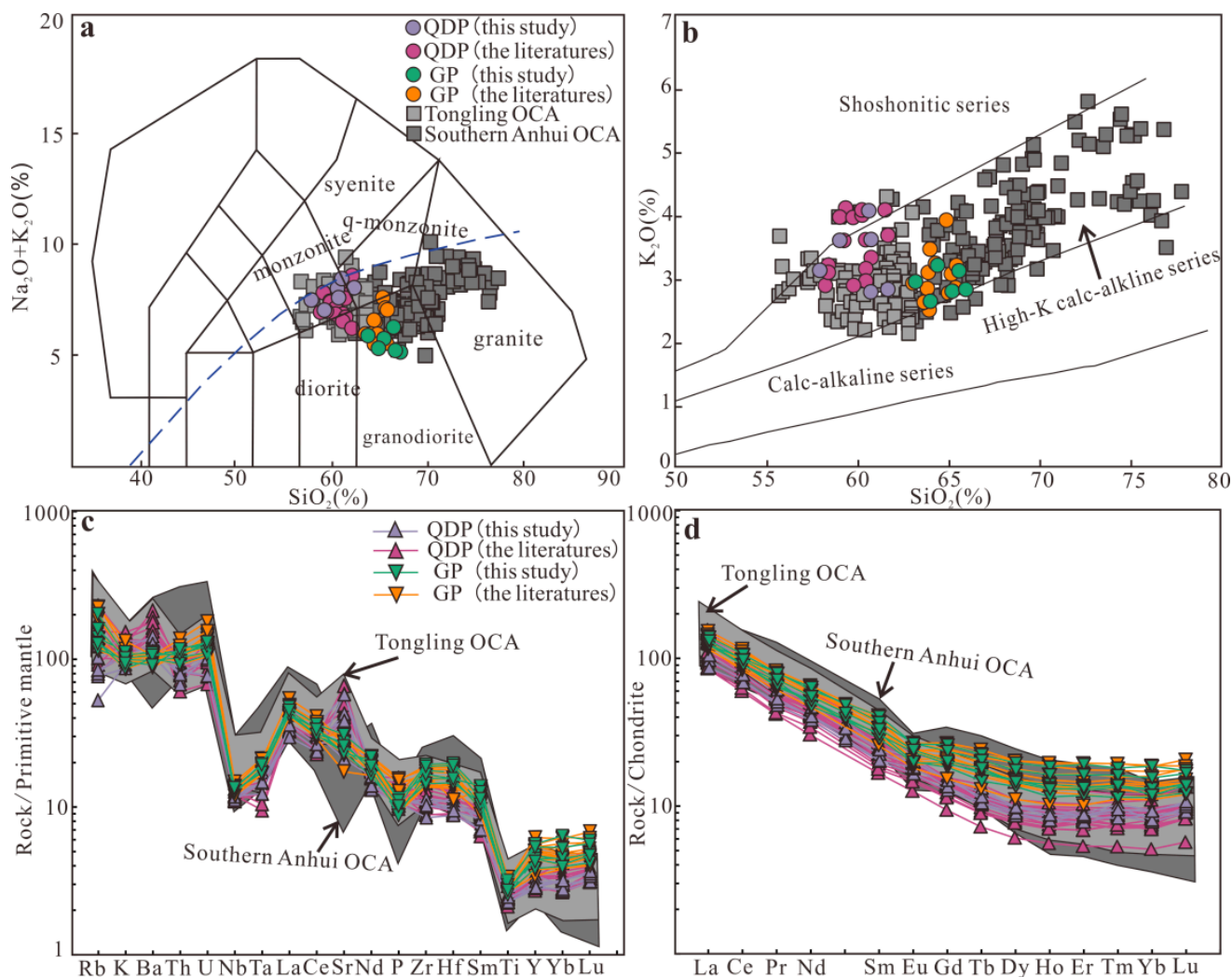


Figure 4. (a) Total alkali versus silica (TAS) diagram (modified from [16]); (b) SiO_2 versus K_2O diagram; (c) Primitive mantle-normalized minor element spidergrams; and (d) Chondrite-normalized REE diagrams for the two ore-bearing intrusive rocks. The blue line in (a) represents the division between alkaline and sub-alkaline. The area below the line is sub-alkaline. The primitive mantle values are from [17], and the chondrite values are from [18]. The QDP is quartz diorite porphyry of the Chating Cu-Au deposit. The GP is granodiorite porphyry of the Magushan Cu-Mo deposit. The OCA is an ore concentration area. The literature of QDP is [4,19]; The literature of the GP is [3,20]. The literature of the Tongling OCA is [21–24]. The literature of Southern Anhui OCA is [25–29].

5.2. Zircon U-Pb Dating

The zircon U-Pb isotopic analysis results of the ore-bearing quartz diorite porphyry (QDP) of the Chating Cu-Au deposit and ore-bearing granodiorite porphyry (GP) of the Magushan Cu-Mo deposit are presented in Supplementary Table S2. Representative analyzed spots and measured values on CL images are shown in Figure 5. The zircon Th and U contents of the QDP and GP are $66\text{--}1365 \times 10^{-6} \text{ g/g}$ and $35\text{--}2222 \times 10^{-6} \text{ g/g}$, respectively. Th/U ratios are 0.43–1.63, consistent with magmatic zircon ($\text{Th/U} > 0.4$, [30]). The zircon U-Pb weighted mean ages of the QDP and GP are $138.9 \pm 0.8 \text{ Ma}$ (MSWD = 0.56, $n = 30$) and $132.2 \pm 1.3 \text{ Ma}$ (MSWD = 0.68, $n = 25$), respectively. The results are consistent with the previous studies [2–4,19,31] and indicate the magma emplacement occurred during the Early Cretaceous.

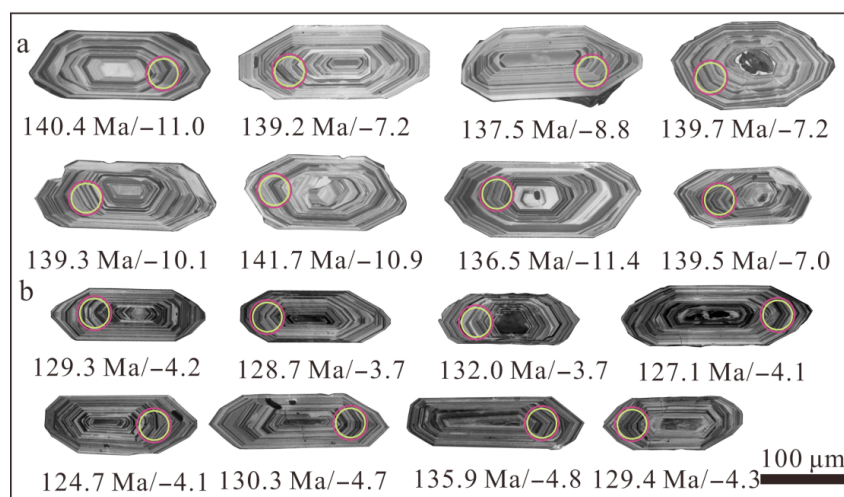


Figure 5. Zircon CL images, U-Pb ages, and Hf isotopic compositions of the ore-bearing intrusive rocks. (a) The quartz diorite porphyry of the Chating Cu-Au deposit; (b) The granodiorite porphyry of the Magushan Cu-Mo deposit. The yellow circle denotes the analytical spots of U-Pb ages; the purple circle denotes the analytical spots of Lu-Hf isotopes.

5.3. Sr-Nd-Hf Isotopes

The whole-rock Sr-Nd and zircon Hf isotope analysis results of the ore-bearing quartz diorite porphyry (QDP) of the Chating Cu-Au deposit and ore-bearing granodiorite porphyry (GP) of the Magushan Cu-Mo deposit are presented in Supplementary Table S3. The QDP has slightly low I_{Sr} values of 0.7064–0.7068 and $\epsilon_{Nd}(t)$ values of −8.5 to −7.3 (Figure 6), consistent with the previous studies (I_{Sr} = 0.7064–0.7069, $\epsilon_{Nd}(t)$ = −9.3–−7.4; [3,19]). The GP has slightly high I_{Sr} values of 0.7079–0.7081 and $\epsilon_{Nd}(t)$ values of −5.7 to −5.4 (Figure 6), consistent with the previous studies (I_{Sr} = 0.7079–0.7086, $\epsilon_{Nd}(t)$ = −6.0–−5.4; [31,32]).

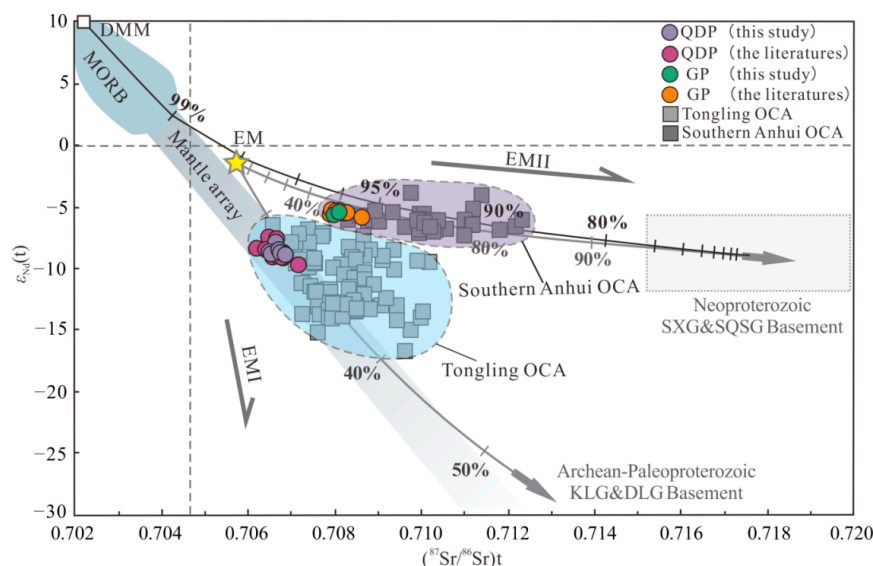


Figure 6. Diagram of Sr-Nd isotopic compositions of the ore-bearing intrusive rocks in the Chating Cu-Au deposit (QDP) and Magushan Cu-Mo deposit (GP). Data sources: MORB, EM I, and EM II are from [33]; DMM is from [34]; EM (yellow star) is from [23]. The Neoproterozoic SXG & SQSG basement (Shangxi Group and Shuangqiaoshan Group) are from [35]; Archean–Paleoproterozoic KLG & DLG basement (Kongling Group and Dongling Group) are from [36,37]. The literature of QDP is [4,19]; The literature of the GP is [3,20,31]; The literature of the Tongling OCA is [38–40]; The literature of Southern Anhui OCA is [41,42].

Representative zircon Hf isotope analyzed spots and measured values on CL images are shown in Figure 5. For the QDP, the zircons give measured $^{176}\text{Hf}/^{177}\text{Hf}$ values that range from 0.282358 to 0.282499 and $\epsilon_{\text{Hf}}(t)$ values that range from -11.9 to -7.0 (average -9.2), corresponding to two-stage Hf model ages (T_{DM2}) of $1.63 - 1.94$ Ga (average 1.77 Ga), consistent with the previous studies ($\epsilon_{\text{Hf}}(t) = -12.1 - -6.7$, $T_{\text{DM2}} = 1.32 - 1.95$ Ga; [3,11,19]). For the GP, the zircons give measured $^{176}\text{Hf}/^{177}\text{Hf}$ values that range from 0.282542 to 0.282602 and $\epsilon_{\text{Hf}}(t)$ values that range from -5.7 to -3.6 (average -4.5), corresponding to two-stage Hf model ages (T_{DM2}) of $1.41 - 1.54$ Ga (average 1.46 Ga), consistent with the previous studies ($\epsilon_{\text{Hf}}(t) = -5.3 - -2.1$, $T_{\text{DM2}} = 1.32 - 1.52$ Ga; [31,32]).

6. Discussion

6.1. Magmatic Processes and Sources

The ore-bearing quartz diorite porphyry (QDP) of the Chating Cu-Au deposit and ore-bearing granodiorite porphyry (GP) of the Magushan Cu-Mo deposit were formed during the Early Cretaceous, belonging to the sub-alkaline high-K calc-alkaline series. The rocks are enriched in LILEs (e.g., K, Rb, Sr, Ba) and LREE, while being depleted in HFSEs (e.g., Nb, Ta, Ti). They display right-leaning REE patterns with minor Eu anomalies. Clearly, the whole-rock geochemical characteristics indicate that the two ore-bearing intrusions were formed at the same diagenetic ages and tectonic settings. The sources of diagenetic material and diagenetic mechanism of the two ore-bearing intrusions are also similar. However, the whole-rock Sr-Nd isotopes and zircon Hf isotope analysis results of the QDP and GP are obviously different, which indicates the diagenetic materials and magmatic processes are also different. The differences may further lead to different metallogenic specializations, showing that the Chating deposit is enriched in Cu and Au, while the Magushan deposit is enriched in Cu and Mo.

Geochemical variations in magmatic rocks can be attributed to source heterogeneities and various magmatic processes such as fractional crystallization (FC) of the parental magma, different degrees of partial melting, and magma mixing [23,43]. Trace element and major element–isotope chemical variation diagrams can be employed to discriminate between different types of magmatic processes [38,41,44,45]. On the La/Sm vs. La diagram (Figure 7), as the La contents increase in the QDP and GP, the La/Sm values also clearly increase, clearly demonstrating that the chemical variations of the QDP and GP are dominantly the result of assimilation–fractional crystallization (AFC). On the $(^{87}\text{Sr}/^{86}\text{Sr})$ vs. $100,000/\text{Sr}$ and $\epsilon_{\text{Nd}}(t)$ vs. $1000/\text{Nd}$ discrimination diagrams (Figure 8), the samples of QDP and GP mostly plot between the trends for assimilation and FC, with a closer affinity to assimilation. Therefore, assimilation processes rather than FC played a major role in the differences of isotopic compositions between the QDP and GP.

The Sr-Nd isotopic composition is one of the most effective tracing methods for determining the source materials of granitoids [33,35]. Figure 6 shows the samples for both deposits mostly plotted between the fields of enriched lithospheric mantle, Neoproterozoic basement, and Archean–Paleoproterozoic basement. However, the ore-bearing quartz diorite porphyries (QDP) of the Chating Cu-Au deposit are closely related to the Archean–Paleoproterozoic basement, and the ore-bearing granodiorite porphyries (GP) of the Magushan Cu-Mo deposit are closely related to the Neoproterozoic basement (Figure 6). The characteristics reflect the mantle-derived materials of the two ore-bearing intrusive rocks, which were both derived from the enriched mantle, but the crust-derived materials are significantly different; that is, the QDP is mainly from the Archean–Paleoproterozoic crust (e.g., Kongling and Dongling Groups), and the GP is mainly from the Neoproterozoic crust (e.g., Shangxi, Shuangqiaoshan, and Shuangxiwu Groups).

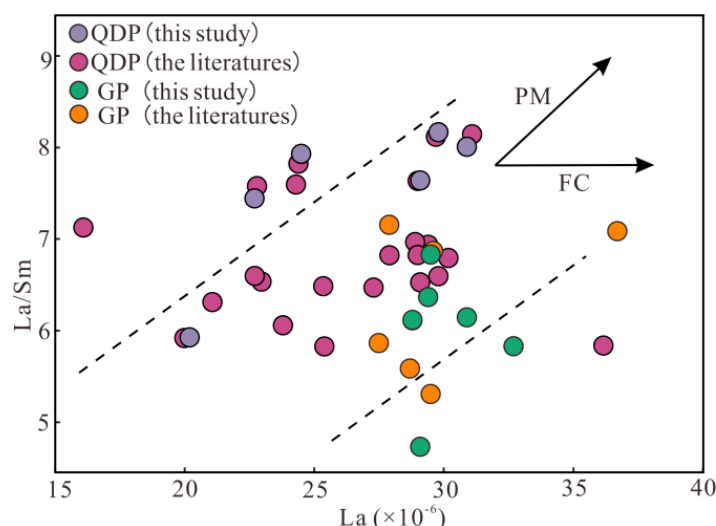


Figure 7. La versus La/Sm diagram for the ore-bearing intrusive rocks in the Chating Cu-Au deposit (QDP) and Magushan Cu-Mo deposit (GP). Data sources: The literature of QDP is [4,19]; The literature of the GP is [3,20,31]. PM = partial melting; FC = fractional crystallization. The dotted lines represent changing trend presented by the samples.

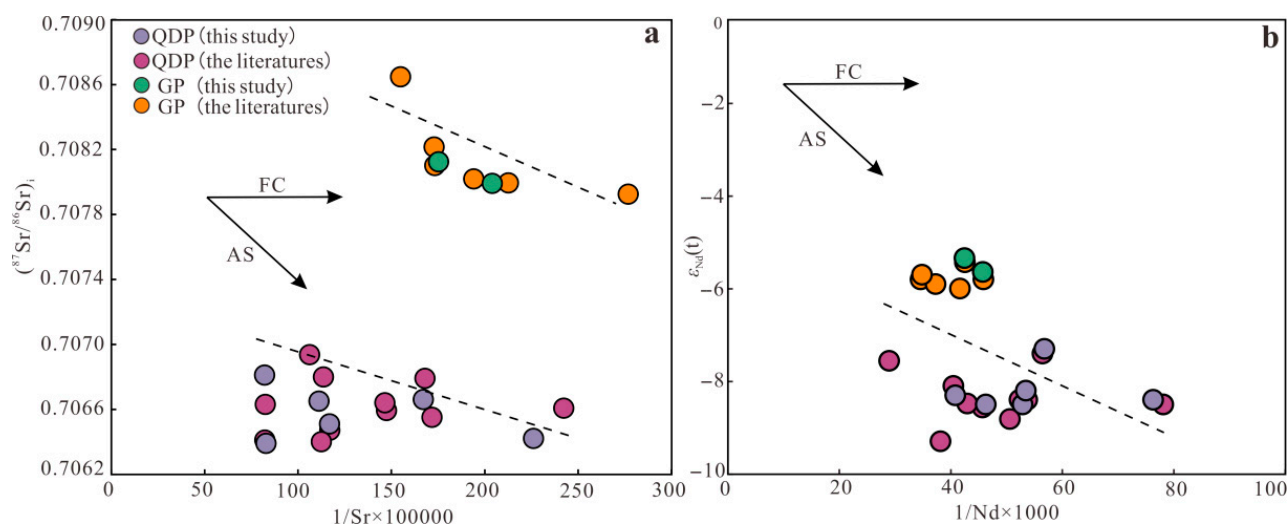


Figure 8. (a) $1/\text{Sr} \times 100,000$ versus $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and (b) $1/\text{Nd} \times 1000$ versus $\epsilon_{\text{Nd}}(t)$ plots for the ore-bearing intrusive rocks in the Chating Cu-Au deposit (QDP) and Magushan Cu-Mo deposit (GP). Data sources: The literature of QDP is [4,19]; The literature of the GP is [3,20,31]. AS = assimilation; FC = fractional crystallization. The dotted lines represent changing trend presented by the samples.

Zircon Hf isotopic composition and Hf model ages are also effective tracing methods for determining the source materials of granite [46]. The QDP and GP zircon $\epsilon_{\text{Hf}}(t)$ values range from -12.1 to -6.7 and from -5.7 to -3.6 , respectively. In the zircon U-Pb ages versus $\epsilon_{\text{Hf}}(t)$ value diagram (Figure 9), the samples mostly plot between the fields of Chondrite Uniform Reservoir (CHUR) and 2.0 Ga crustal evolution lines, clearly indicating that the protolith crust-derived magma was derived from ancient crustal materials. Figure 9 also shows that the QDP samples are under the 1.8 Ga crustal evolution lines, while the GP samples are above the 1.8 Ga crustal evolution lines. In addition, the two-stage Hf model ages ($T_{\text{DM}2}$) of the QDP and GP are 1.63–1.94 Ga and 1.41–1.54 Ga, respectively. The difference of zircon $\epsilon_{\text{Hf}}(t)$ value and $T_{\text{DM}2}$ also reflects the ancient crust materials in the QDP and GP sources, which are the Archean–Paleoproterozoic crust and Neoproterozoic crust, respectively.

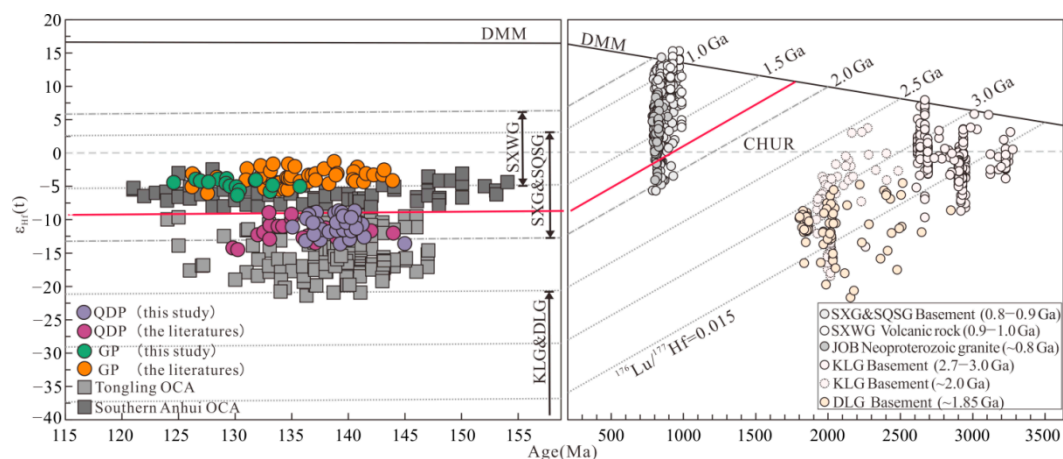


Figure 9. Plots of zircon U-Pb age versus $\epsilon_{\text{Hf}}(t)$ value of the ore-bearing intrusive rocks in the Chating Cu-Au deposit and Magushan Cu-Mo deposit. Data sources: The Neoproterozoic SXG and SQSG basement (Shangxi Group and Shuangqiaoshan Group) are from [47–50]; SXWG (Shuangxiwu Group) is from [51]; The Archean–Paleoproterozoic KLG and DLG basement (Kongling Group and Dongling Group) are from [52–54]; The data of the JOB Neoproterozoic granite are from [55–57]. The literature of QDP is [4]; The literature of the GP is [3]. The literature of the Tongling OCA is [58–61]; The literature of Southern Anhui OCA is [62–64].

Our results suggest that in the sources of the QDP and GP, the mantle-derived magma originated from enriched mantle, while the crust-derived magma was derived from the partial melting of the Archean–Paleoproterozoic crustal materials and Neoproterozoic crustal materials, respectively.

6.2. Basement Compositional Effects on Magmatism and Metallogenesis

The Chating porphyry deposit (primarily Cu-Au) and the Magushan skarn deposit (primarily Cu-Mo) are both closely associated with the Mesozoic magmatic activity [2,3,5,11]. The characteristics correspond to the Tongling Cu-Au polymetallic ore concentration area in the MLYB and the southern Anhui Mo polymetallic ore concentration area in the Jiangnan orogen, respectively.

Previous studies have discussed petrogenesis and the tectonic setting of the magmatic rocks in the Tongling and southern Anhui ore concentration areas and proposed several models as follows: (1) partial melting of delaminated lower continental crust in an intracontinental setting [65–67]; (2) basaltic magma derived from mantle assimilating the lower continental crust in an intracontinental setting [21,68–70]; (3) partial melting of the subducting oceanic crust, or metasomatized-enriched mantle, by fluids derived from Mesozoic Paleo-Pacific ocean plate subduction [71–78]; (4) partial melting of ancient metasomatized-enriched mantle and mixing with crust-derived magmas [79–84].

However, the subduction setting is not supported by the following points: (1) The Mesozoic magmatic rocks of the MLYB stretched 1000 km from the continental margin, significantly exceeding the typical width of a subduction zone (300–400 km) [69]; the complex spatial-temporal variations in compositions and rock types are difficult to explain by a simple continental arc model [81]; geophysical evidence indicates that the Paleo-Pacific plate subduction served as a geodynamic mechanism to the MLYB, but no direct material input [83]; the Sr-Nd isotopic compositions of the Mesozoic magmatic rocks and the common mafic enclaves hosted in the intrusive rocks in the MLYB indicate magma was derived from a crust–mantle mixture [6,11,19,24,51]. The partial melting of the lower crust fails to explain these characteristics. Therefore, although the petrogenesis and tectonic setting of these magmatic rocks remain debated, the consensus is that these intru-

sive rocks were derived from a crust–mantle mixture with predominant mantle-derived materials [36,65,85,86].

Whole-rock Sr–Nd and zircon Hf isotopic compositions indicate that the source crustal materials of the Mesozoic intrusive rocks in the Tongling and the southern Anhui ore concentration area respectively correspond to the Archean–Paleoproterozoic basement, for example, the Kongling and Dongling Groups [49,53,54,87], and the Neoproterozoic low-grade metamorphic basement, such as the Shangxi, Shuangqiaoshan, and Shuangxiwu Groups [88–90]. As discussed above, the sources for the intrusive rocks in both the Tongling and southern Anhui ore concentration areas are predominantly mantle-derived materials, while the mantle materials are characteristically enriched in Cu and Au [83,91,92]. Consequently, the metallogenic elements of deposits related to these intrusive rocks are Cu and Au. However, crust-derived materials of the intrusive rocks in the Tongling and southern Anhui ore concentration areas are different. The crust-derived materials of the latter are Neoproterozoic basement, which is characteristically enriched in Mo [93–95]. Therefore, the southern Anhui ore concentration area is dominated by Mo polymetallic deposits.

Previous studies indicate that the source could influence enrichment of metallogenic metal elements and the magma oxidation state [96], further leading to the spatial decoupling of metallogenic metal elements [97]. In recent years, many studies have explored reasons for the diversity of metallogenic metal elements in one area. For instance, deposits in the southern Hunan area mainly include Cu–polymetallic deposits and W–Sn deposits, and the reason for the diversity of their metallogenic metal elements is mainly the different magma sources of the ore-bearing intrusive rocks [98,99]. Obviously, whether it is the Tongling ore concentration area in the MLYB or the southern Anhui ore concentration area in the Jiangnan orogen, and whether it is the Chating deposit or the Magushan deposit, the different Sr–Nd–Hf isotopic compositions of the ore-bearing intrusive rocks reveal the differences in the magma sources. However, the differences for the source crustal materials of the two adjacent metallogenic belts and the two adjacent deposits in the Nanling–Xuancheng ore concentration area (NXOR) are eventually controlled by the regional crustal basement (Figure 10).

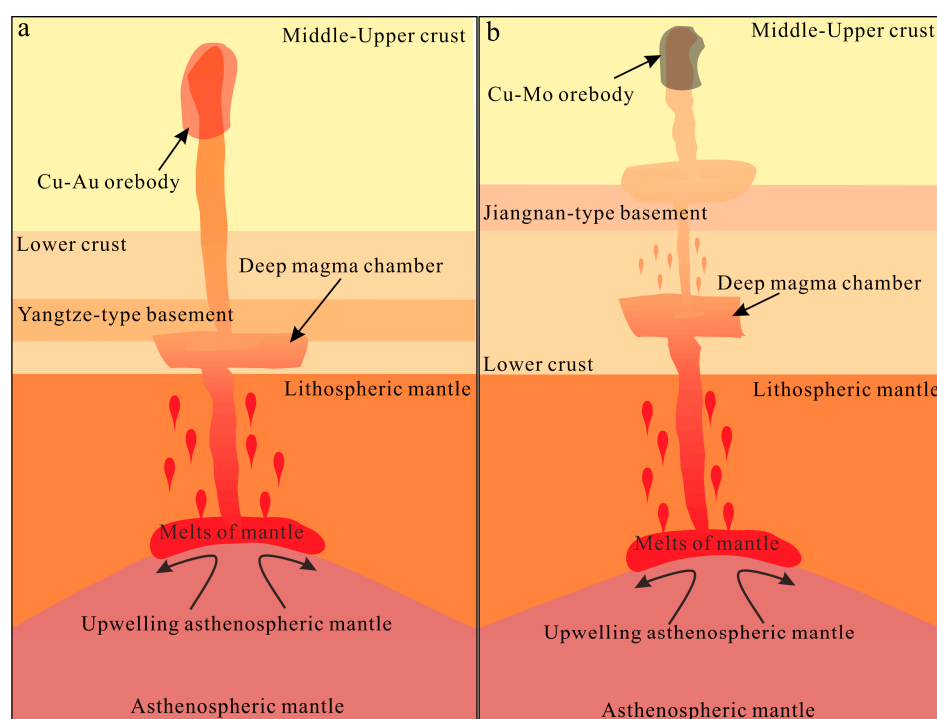


Figure 10. Models of the deep process of (a) Chating Cu–Au and (b) Magushan Cu–Mo deposits.

The Pre-Sinian basement of the MLYB and even the northern margin of the Yangtze Block have been debated. Some researchers suggest that the Yangxin (Chongyang)-Changzhou Fault (YCF) is the boundary of the basement, geologically, and the boundary is along the line of Sangzhi-Jianli Hubei Province, Lushan Jiangxi Province, Qingyang-Xuancheng Anhui Province, and Changzhou Jiangsu Province, geographically [71,100–102]. The basement for the northwestern part of the YCL is the “Middle-Lower Yangtze type”/“Dongling-Kongling type” basement, represented by the Archean–Paleoproterozoic metamorphic basement of the Dongling, Kongling, and Picheng Groups, and the southeastern part is the “Jiangnan-type” basement, characterized by the Neoproterozoic low-grade metamorphic basement such as the Shangxi, Shuangqiaoshan, Shuangxiwu, and Lengjiayi Groups [100,103,104]. However, the YCF’s precise location in the NXOR (from Xuancheng, Anhui province, to Changzhou, Jiangsu province) remains unclear due to its concealed characteristic [105].

Based on this study, the characteristics of the Chating and Magushan deposits and their ore-bearing intrusive rocks (QDP and GP), located northwest and southeast of the Jiangnan Deep fault, are consistent with those of the Tongling ore concentration area in the Middle-Lower Yangtze River metallogenic belt and the Southern Anhui ore concentration area, respectively. The characteristics indicate the ZWF (Zhouwang fault) in the NXOR, constituting the middle of the YCF, may be offset by the Jiangnan Deep Fault. The ZWF extends from west to east to Zhouwang Village and then is tracked to the Jiangnan Deep fault. After passing through the west of the Magushan deposit, it is tracked to the NW-trending Chaohu-Wuhu fault and continues to extend eastward (Figure 1). Therefore, the metallogenic elements of the Chating deposit and magma sources of its ore-bearing intrusive rocks show similar characteristics with the adjacent Tongling ore concentration area, while those of the Magushan deposit and its ore-bearing intrusive rocks show fundamental consistency with the adjacent Southern Anhui ore concentration area.

7. Conclusions

The ore-bearing intrusive rocks of the Chating Cu-Au and the Magushan Cu-Mo deposits belong to the high-K calc-alkaline rock series. The whole-rock major and trace element compositions, as well as rare earth elements (REE), are similar. However, their whole-rock Sr-Nd and zircon Hf isotopic compositions are obviously different. These characteristics indicate that the magmas of both the Chating and Magushan intrusive rocks were derived from mixture of crustal and mantle sources, with the crustal components for the Chating intrusive rocks originated from Archean–Paleoproterozoic crustal materials (e.g., the Kongling and Dongling Groups), and the crustal components for the Magushan intrusive rocks derived from Neoproterozoic crustal materials (e.g., the Shangxi, Shuangqiaoshan, and Shuangxiwu Groups).

The metallogenic element, Sr-Nd-Hf isotopic compositions, and magma sources of the Chating and Magushan deposits correspond respectively to the Tongling Cu-Au polymetallic ore concentration area and the Southern Anhui Mo polymetallic ore concentration area. These characteristics reflect that the Nanling-Xuancheng ore concentration area has dual characteristics of both the Middle-Lower Yangtze River metallogenic belt and the Southern Anhui ore concentration area. Furthermore, the Jiangnan Deep fault in the Nanling-Xuancheng ore concentration area is boundary between the two areas, simultaneously serving as the boundary between the distinct ancient basements.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/min15080837/s1>. All data generated and analyzed during this study are included in this article and its Supplementary Material file: Table S1: Whole-rock major and trace elements for ore-bearing quartz diorite porphyry of the Chating Cu-Au deposit and ore-

bearing granodiorite porphyry of the Magushan Cu-Mo deposit; Table S2: The zircon U-Pb isotopic analysis results of the ore-bearing quartz diorite porphyry and granodiorite porphyry; Table S3: The whole-rock Sr-Nd and zircon Hf isotopes analysis results of the ore-bearing quartz diorite porphyry and granodiorite porphyry.

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

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