

Article

Contrasting Sources and Related Metallogeny of the Triassic and Jurassic Granitoids in the Chifeng–Chaoyang District, Northern Margin of the North China Craton: A Review with New Data

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Abstract: Understanding of the mechanism between magma sources and metallogeny is still vague. As an important gold and molybdenum producing area, the Chifeng–Chaoyang district, located at the northern margin of the North China Craton (NCC), is a key place for this issue. New geochemical data relating to Taijiying gold-deposit-related granites are presented. These data, coupled with previous studies, are used to explore the relationship between magma sources and mineralization processes. Two major magmatic periods, the Middle Triassic (220–230 Ma) and Late Jurassic (150–160 Ma), are identified based on the compiled data. The Triassic magmatic rocks are mostly fractionated I-type and A-type granites, including monzogranite, biotite granite, and syenogranite. They have low initial $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.7050), moderately enriched $\epsilon_{\text{Nd}}(t) - \epsilon_{\text{Hf}}(t)$ values (−8.5 and −5.6), and relatively young Nd–Hf model ages ($T_{\text{DM}2} - T_{\text{DM}}^{\text{C}}$) (1.47–1.57 Ga). These features indicate that more Archean–Paleoproterozoic mantle-derived materials were involved in their sources. On the other hand, Jurassic granites are high-K calc-alkaline of the calc-alkaline series and mainly consist of granite, monzogranite, leucogranite, and granodiorite. They have high $\text{Na}_2\text{O}/\text{K}_2\text{O}$, Sr/Y , and La/Yb ratios and low Y and Yb contents. The adakitic features suggest the existence of a thickened lower crust. Their significant negative $\epsilon_{\text{Nd}}(t) - \epsilon_{\text{Hf}}(t)$ values (−15.0 and −12.8) and older Nd–Hf model ages ($T_{\text{DM}2} - T_{\text{DM}}^{\text{C}}$) (2.17–2.11 Ga) are consistent with their derivation from thickened ancient lower crust, indicating the initial activation of NCC. It is proposed that the change in the main source resulted from the tectonic transition during the early Mesozoic initial decratonization, that is, from the post-collisional extension to the subduction of the Paleo-Pacific plate beneath the East Asia plate from the Triassic to the Jurassic. Comparative analysis suggests that the medium–large-scale gold deposits with a high grade are closely related to the Triassic granites; however, most molybdenum deposits formed in the Jurassic. The decratonization of the NCC in the early Mesozoic experienced tectonic transition and controlled the gold and molybdenum mineralizations in the different stages by the changing magma sources. This pattern is beneficial to understanding the metallogenesis in the Chifeng–Chaoyang district.

Keywords: magmatic source; metallogenesis; Sr–Nd–Hf–O isotopes; Chifeng–Chaoyang; North China Craton

1. Introduction

The distribution patterns of deposits are very important for exploration. Although many methods and parameters have been applied to decipher these rules, the feature of deep sources has been proved to be a good indicator. The transitions in the magma source indicate the changes of tectonic settings and significant mineralization events in

most cases. For example, the switch in the magmatic source from enriched lithospheric mantle to depleted asthenospheric mantle was the most marked change during the NCC cratonic destruction, which promoted large-scale gold deposits. [1–3]. Therefore, the northern margin of the NCC, especially in the eastern section, is a good place to explore the relationship between the deep magmatic source and metallogenesis. This is because of the widespread Mesozoic felsic intrusive rocks and contemporaneous mineralization in this region.

The Chifeng–Chaoyang district is located in the eastern NCC, which was affected by the Central Asian Orogenic Belt (CAOB) and the Pacific plate in the Mesozoic (Figure 1a). The Paleozoic–Mesozoic magmatic rocks were emplaced, as well as many medium–large gold and molybdenum deposits (Figure 1b). Yang et al. (2017) preliminarily divided this district into four Nd isotope areas according to the model ages (T_{DM}) of the Phanerozoic granitoids [4]. In the southeastern margin of the NCC, Deng et al. (2018) proposed that the porphyry and porphyry-skarn Cu (–Au–Mo) deposits are associated with Paleoproterozoic to Mesoproterozoic reworked crustal components with minor mantle material [5]. The Jiaodong-type Au and porphyry-skarn Mo (–W–Cu) deposits are associated with Archean–Paleoproterozoic reworking crustal components. Thus, the common relationship between the crustal materials and the mineralization in this area remains unclear. The Mo mineralization is closely related to the small granitic bodies with aged continental component sources, and the Mo deposits are mainly located in the oldest terranes [6]. Some researchers proposed that the hydrated mantle wedge is the source of gold deposits through local and rapid devolatilization, which suggests a juvenile source. Field works and analysis displayed high grades of Taijiying gold distributed along the granite dikes. Previous research also suggested that magmatism related to granite porphyries provided fluids and sources for the gold mineralization systems [7]. However, the kind of source controlling the Taijiying gold deposits is still unclear. In this paper, we present new petrology, U–Pb zircon ages, geochemistry, whole-rock Sr–Nd isotopes, and zircon O–Hf isotope data for the Taijiying granite porphyries (Figure 1b) and submit published data for the Triassic and Jurassic felsic magmatic rocks in the Chifeng–Chaoyang district [8]. These results can help us to better understand the sources of the granitoids and their effects on Mo and Au mineralization.

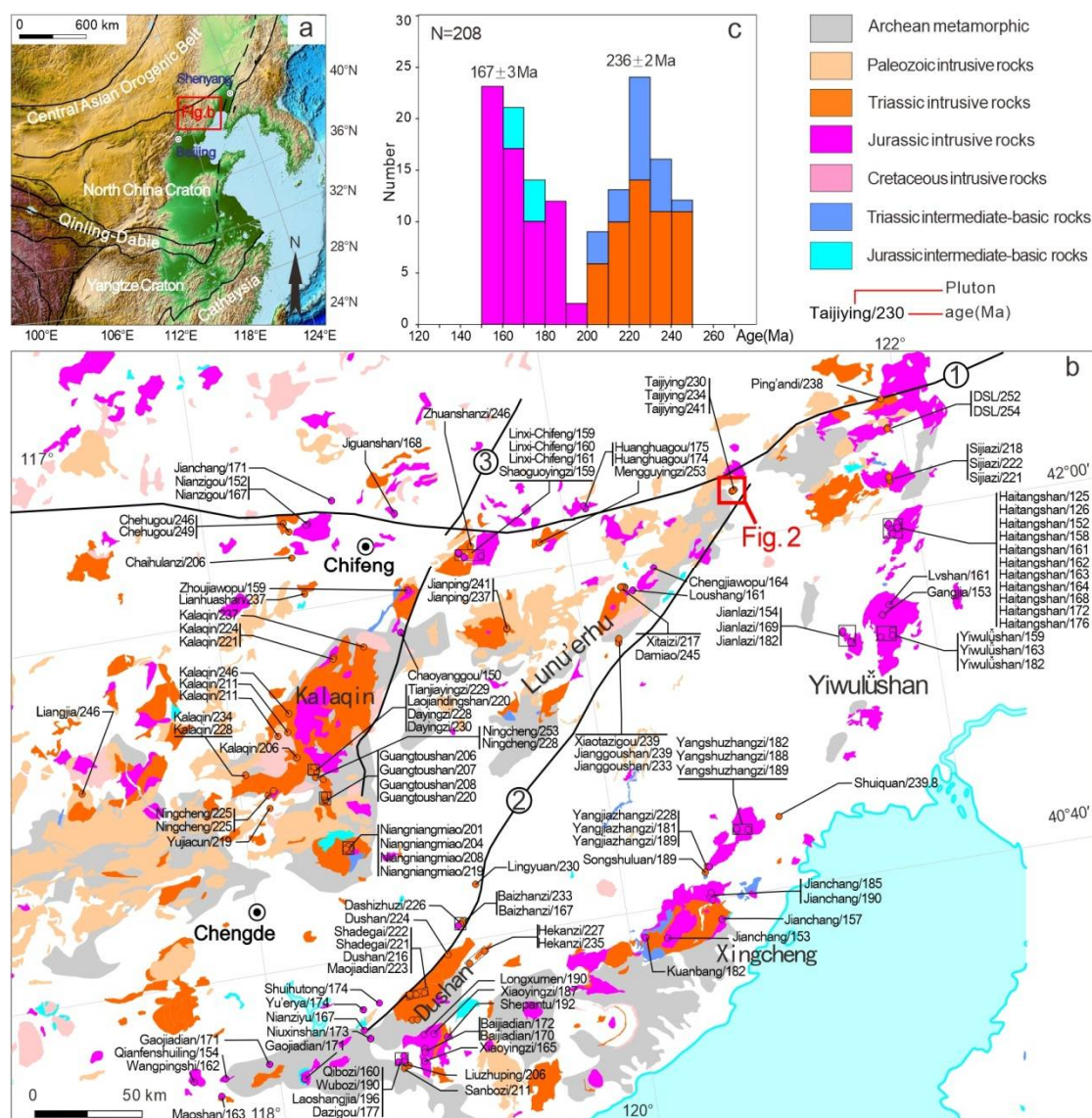


Figure 1. (a) Sketchmap of North China Craton (Wu et al., 2019); (b) outline map of Phanerozoic granitoids in Chifeng–Chaoyang and adjacent areas [8,9]. ①—Chifeng–Kaiyuan fault; ②—Lingyuan–Beipiao fault; ③—Honghan–Balihan fault; (c) Histogram of ages of intrusive rocks in two episodes of Chifeng–Chaoyang and adjacent areas (supplementary data are listed in the Supplementary Materials).

2. Geological Background

The triangular NCC, with an area of ca. 1,500,000 km², is bounded by the CAO to the north, Sulu UHP belt to the east, Qilianshan Orogen to the west, and Qinling–Dabie orogenic belt to the south and is one of the oldest cratons in the world ([10,11]; Figure 1a). The craton had a prominent peak of crustal growth activity during the Neoproterozoic ca. 2.5–2.7 Ga [12]. The amalgamation of the eastern and western blocks along the NS-trending Trans-North China Orogen is generally considered to have occurred during the late Paleoproterozoic ~1.85 Ga [13,14]. In ca. 1.32 Ga, a large number of tholeiitic diabase sills or dyke swarms constituted a mid-Mesoproterozoic large igneous province in the northern NCC [15]. The multiple-stage lithospheric thinning and destruction of the NCC started from the initiation of massive circum-craton Phanerozoic subduction and collisional orogenies. In the early Paleozoic, the Qilian oceanic plate subduction and collision with the Kunlun–Qaidam Block occurred [16]. In the late Paleozoic, closure of the Paleo-Asian

Ocean and collision with the Siberia Craton happened along the northern margin of the NCC [17]. The deep subduction and collision of the Yangtze Block further destructed the NCC during the late Permian to Triassic [18]; subsequently, the Paleo-Pacific plate's westward subduction or Yangzi Craton collision started in the Early Jurassic [19]. The Pacific plate's ongoing westward subduction during the Cretaceous was the peak stage of decratonization.

The Chifeng–Chaoyang district occupies the eastern segment of the northern NCC, which is dominated by the EW-trending Chifeng–Kaiyuan fault, NE-trending Lingyuan–Beipiao fault and NNE-trending Honghan–Balihan fault (Figure 1b). The Chifeng–Kaiyuan fault divides the Hinggan–Mongolian Orogenic Belt (the middle and east part of the CAO) from the NCC [20]. The Lingyuan–Beipiao fault, more than 1000 km in length, extends from Chengde to Beipiao city. The Honghan–Balihan fault consists of a ~3 km thick ductile and ductile-brittle shear zone passing upward into a ~100 m thick brittle chloritic breccia and a ~0.5 m thick microbreccia with fault gouges [20,21]. These compressional and shearing faults have existed since the Paleoproterozoic and have undergone multiple reactivations in the Paleozoic, Mesozoic, and especially the Yanshanian period [22]. The EW-striking faults are the earliest faults in the region, which are mostly cut by the later NE-striking faults. They divide the study area into several rhombic blocks where many gold and molybdenum deposits and granitoids have been discovered [22].

This district mainly consists of Precambrian basement rocks and Paleozoic to Mesozoic granitoids. The Precambrian basement rocks belong to the Neoproterozoic to Paleoproterozoic Jianping, Qianxi, and Zunhua groups, which consist of sedimentary and volcanic sequences and tonalite–trondhjemite–granodiorite (TTG) gneisses with different degrees of migmatization [22–24]. These successions were further metamorphosed to granulite phases ca. 2485 Ma and were retrograded to the greenschist phases ca. 2450–2401 Ma [23,25]. The Paleozoic rocks are distributed in the Aohanqi area, mainly belonging to a set of continental volcanic-sedimentary strata [22]. Mesozoic volcanic rocks are continental volcanic rocks which mainly consist of basalt, basaltic andesite, andesitic breccias, and tuff [26]. The Cenozoic strata are mainly residual slope and alluvial sands and loess-like sub-sandy soil.

More Triassic and Jurassic intrusions have been discovered through various dating methods (Supplementary Table S1 and Figure 1b). The intrusions in this area mainly comprise three NE-trending uplift belts, including the Kalaqin, Lunu'erhu, and Yiwulüshan metamorphic core complexes (MCCs) to the north and the Dushan composite batholiths, Xingcheng, to the south (Figure 1b). Triassic granitoids are mainly distributed in Kalaqin, Lunu'erhu, while the majority of Jurassic granites occur in the Xingcheng, Yiwulüshan MCC. The Triassic intrusions and dikes, including granodiorite, alkalic granite, and minor basic and ultrabasic rocks, are mainly distributed in the area of southern Chifeng and eastern Chengde city. The Dushan monzogranite–granodiorite, Dashizhuizi granite, Panshan monzogranite/granite, and Baizhangzi granite are well studied [27–29]. The EW-trending contemporaneous alkaline rocks belt consists of Hekanzi nepheline syenite, Guangtoushan alkaline granite, and Sungezhuang alkaline syenite [30–32]. The Jurassic plutons mainly consist of granite, granodiorite, and monzogranite exposed along regional faults, which present Qingshankou granite, Yu'erya granite, Niuxinshan granite, Jianchang–Jiumen monzogranite, Xiaojiayingzi batholiths, and Gaojiadian quartz diorite [33] (Supplementary Table S1). Generally, Triassic and Jurassic granitoids exhibit different preferences for emplacement locations [34]. Triassic granites are mostly discovered in the northern margin, close to the suture zone between the CAO and NCC, while Jurassic granites are located in the southeast, where the area was affected by the westward subduction of the Paleo-Pacific Ocean plate.

3. Sources and Gold Mineralization of Taijiying Granite Porphyries

The granite porphyries are characterized by high-silicon dike. They mainly consist of brick-red granite porphyry, which is closely related to Taijiying gold mineralization (Figure 2a–c). Field works and analysis displayed high grades of gold distributed along

the granite dikes. Previous research also suggested that magmatism related to granite porphyries provided fluids and sources in the process of gold mineralization [7]. However, the kinds of source are still unclear. The outcrop is NE-trending with a length of ca. 800 m and a width of more than 10 m (Figure 2a). This dike intruded into the Archean metamorphic rocks and Cenozoic strata with clear contact lines. The granite porphyries have a medium-to-fine-grained porphyritic texture. Thirteen samples were collected from the drilling cores and outcrops. They mainly consisted of 30%–40% phenocrysts by volume (Figure 2d–f). The phenocrysts consisted of quartz (3%–5%), perthite (5%–8%), and platy plagioclase (ca. 1%). The quartz was generally euhedral or anhedral, 0.5–1.0 mm in size, and was surrounded by recrystallized groundmass. The perthite had clear streaks with argillic alteration. The plagioclase (0.2–0.5 mm) was euhedral with strong argillic alteration and slight sericitization. The minerals in the groundmass were mainly composed of felsic spherulites (70%–75%), plagioclase (8%–10%), sericite (5%–8%), and biotite (less than 1%). The plagioclase crystal was generally the center of spherulite and surrounded by the radially fibrous corpora.

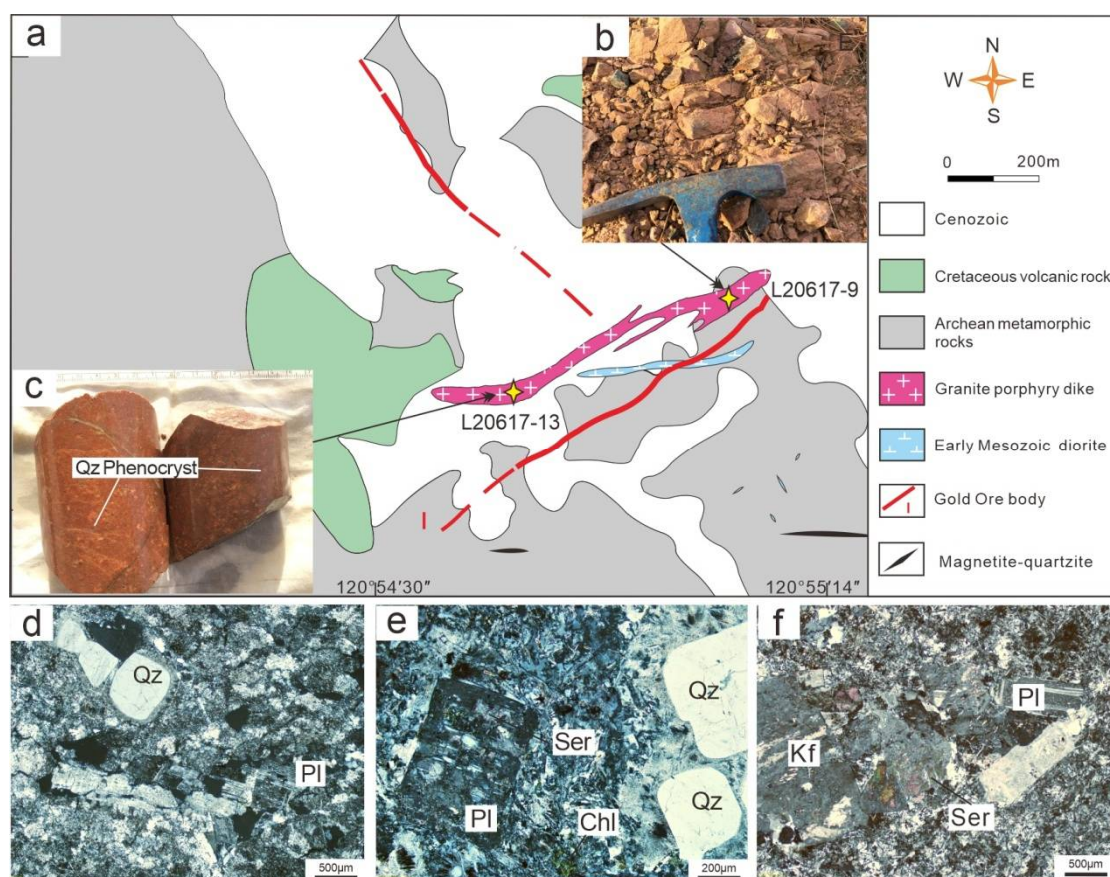


Figure 2. (a) Location of granite porphyry dikes in the Taijiying gold deposit; (b) outcrop of granite porphyry; (c) granite porphyry from drilling core; (d–f) photomicrographs of granite porphyries. Abbreviations: Qtz = quartz, Pl = plagioclase, Ser = sericite, Chl = chlorite, Kf = K-feldspar.

The zircon U–Pb dating results of Taijiying granite porphyries are listed in Table 1. Concordia diagrams are shown in Figure 3. Sample L20617-9 and L20617-13 exhibited zircons similar in size with lengths of 110–240 µm and widths of 80–160 µm and ratios of 1:1 to 2:1. The Th/U ratios were slightly lower, with values of 0.57 and 0.60, respectively, and exhibited a positive correlation, reflecting their magmatic origin [35,36]. For sample L20617-9, 25 spots on 25 zircon grains were analyzed by LA-ICP-MS, and the results are plotted on concordia diagrams in Figure 3. All analyses were concordant except the spot

L20617-9-02, which showed extremely low concordance for the influence of inclusion in the zircon grain. The others yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 234 ± 1 Ma (95% confidence, MSWD = 1.1). In sample L20617-13, 27 spots on 27 zircon grains were chosen for measurement by LA-ICP-MS. The 23 analyses results were concordant and yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 230 ± 2 Ma (95% confidence, MSWD = 1.9) which represented the emplacement age of the granite porphyry. Two granite porphyry samples had a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age ranging from ca. 230 to 234 Ma, suggesting that the emplacement of granitoid dikes occurred during the Middle Triassic period.

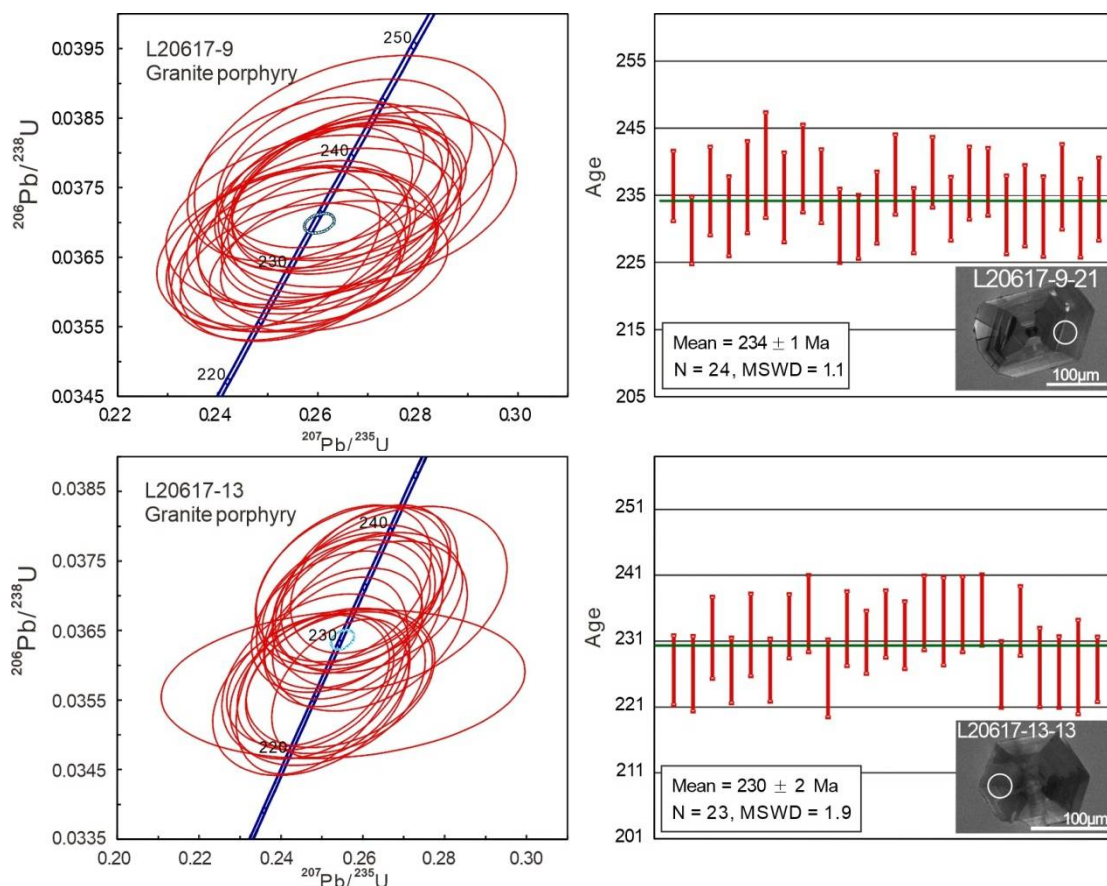


Figure 3. U–Pb concordia plots and age data histograms for samples L20617-9 and L20617-13 (granite porphyry dikes) in Taijiying gold deposit.

The geochemical results for the 14 Taijiying granite porphyry samples are presented in Table 2. The Taijiying granite porphyries had a high and narrow range of SiO_2 contents (69.0–77.6 wt%), and their mean ($\text{K}_2\text{O} + \text{Na}_2\text{O}$) value was 7.47 wt%. They had low Fe_2O_3 (0.76–1.88 wt%), MgO (0.18–0.61 wt%), CaO (0.12–1.23 wt%), and TiO_2 (0.09–0.12 wt%) contents. The samples were plotted in the high-K calc-alkaline field (Figure 4a). Al_2O_3 contents were concentrated in the range of 11.4 wt% to 12.6 wt% and were plotted in the metaluminous and peraluminous fields, with A/CNK values (molar ratios of $\text{Al}_2\text{O}_3/\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O}$) of 0.96 to 1.36, except the extremely low value of 0.58 (Figure 4b). In the Harker diagrams, the granite porphyries were plotted in a straight line (Figure 5). All samples exhibited light rare earth element (LREE) enrichment, with $(\text{La}/\text{Yb})_N$ ratios of 7.6 to 22.0 (mean = 18.3) (Figure 6b). Several samples had high $(\text{La}/\text{Yb})_N$ ratios of greater than 20, including L20617-7, L20617-8, and L20617-14. The samples of different ages all exhibited significant negative Eu anomalies, with δEu values of 0.10–0.40 (mean = 0.16). On the primitive, mantle-normalized trace element spider diagram (Figure 6b), all samples exhibited large ion lithophile element (LILE) (such as Rb and Th) enrichments and high

field strength element (HFSE) (such as Nb, Ta) depletions with negative Ba, Sr, Eu, Nb, Ta, and P anomalies. These granite porphyries were plotted between the A-type and I-type granite fields in Figure 7. It was difficult to distinguish between fractionated I-type granites and A-type granites due to their similar features. However, based on the lower zircon saturation temperature (mean = 810 °C) and FeOT/MgO ratios (mean = 7.5), it is reasonable to conclude that the Taijiying granite porphyries are fractionated I-type granites.

Table 1. LA-ICP-MS zircon U–Pb data of the granite porphyry in Taijiying gold deposit.

Spots	Content (ppm)				Ratios						Age					
	Total Pb	²³² Th	²³⁸ U	Th/U	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ
L20617-9, granite porphyry, 24 spots, weighted mean age = 234.2 ± 1.1 Ma, MSWD = 1.07																
L20617-9-01	86.32	1218	1750	0.7	0.0499	0.0016	0.2595	0.0079	0.0374	0.0004	191	72.21	234	6.4	236	2.64
L20617-9-03	58.06	682	1236	0.55	0.0498	0.0023	0.2545	0.009	0.0363	0.0004	183	107.39	230	7.28	230	2.53
L20617-9-04	61.48	640	1289	0.5	0.0505	0.002	0.2639	0.0095	0.0372	0.0005	217	94.43	238	7.61	236	3.32
L20617-9-05	91.15	1437	1836	0.78	0.0487	0.0017	0.251	0.0087	0.0366	0.0005	200	81.47	227	7.08	232	2.97
L20617-9-06	62.56	702	1299	0.54	0.0513	0.0021	0.2684	0.0108	0.0373	0.0006	254	96.28	241	8.67	236	3.44
L20617-9-07	50.1	477	1051	0.45	0.0501	0.0026	0.2663	0.0127	0.0379	0.0006	198	124.98	240	10.18	240	3.94
L20617-9-08	64.96	771	1333	0.58	0.0505	0.0022	0.2622	0.0108	0.0371	0.0005	220	102.76	236	8.69	235	3.36
L20617-9-09	55.89	470	1186	0.4	0.0503	0.002	0.2653	0.0104	0.0378	0.0005	209	87.95	239	8.38	239	3.27
L20617-9-10	60.91	665	1250	0.53	0.0509	0.0018	0.2658	0.0094	0.0373	0.0004	235	86.1	239	7.53	236	2.77
L20617-9-11	46.02	510	1005	0.51	0.0502	0.0019	0.2541	0.0096	0.0364	0.0004	211	88.88	230	7.75	230	2.76
L20617-9-12	62.63	709	1321	0.54	0.0519	0.002	0.2621	0.0097	0.0364	0.0004	280	87.03	236	7.84	230	2.39
L20617-9-13	70.83	906	1447	0.63	0.0504	0.0017	0.257	0.0085	0.0368	0.0004	213	43.51	232	6.91	233	2.69
L20617-9-14	59.51	778	1205	0.65	0.0494	0.0018	0.2575	0.0097	0.0376	0.0005	165	87.95	233	7.8	238	2.99
L20617-9-15	80.24	928	1673	0.55	0.0518	0.0017	0.2622	0.0088	0.0365	0.0004	276	69.44	236	7.12	231	2.44
L20617-9-16	84.37	1088	1689	0.64	0.0505	0.0018	0.2635	0.0093	0.0377	0.0004	220	49.07	237	7.44	238	2.65
L20617-9-17	97.14	1446	1926	0.75	0.0509	0.0016	0.2601	0.0079	0.0368	0.0004	239	70.36	235	6.4	233	2.39
L20617-9-18	85.92	1310	1687	0.78	0.0507	0.0016	0.2638	0.0086	0.0374	0.0004	228	74.06	238	6.91	237	2.72
L20617-9-19	84.23	1161	1669	0.7	0.051	0.0018	0.2661	0.0096	0.0375	0.0004	239	83.32	240	7.69	237	2.54
L20617-9-20	55.45	609	1189	0.51	0.0498	0.0022	0.2543	0.0099	0.0367	0.0005	187	103.69	230	7.98	232	2.94
L20617-9-21	51.08	537	1093	0.49	0.0508	0.0022	0.2612	0.0112	0.0369	0.0005	232	101.84	236	9	233	3.03
L20617-9-22	92.16	1452	1840	0.79	0.0498	0.0026	0.2559	0.0115	0.0366	0.0005	183	120.36	231	9.3	232	3.01
L20617-9-23	39.61	254	882	0.29	0.0517	0.0024	0.2695	0.0123	0.0373	0.0005	333	104.62	242	9.85	236	3.19
L20617-9-24	49.55	313	1134	0.28	0.0506	0.0022	0.258	0.0104	0.0366	0.0005	233	98.14	233	8.43	232	2.94
L20617-9-25	37.27	422	804	0.52	0.0497	0.0022	0.2578	0.0115	0.037	0.0005	189	103.69	233	9.3	234	3.1
L20617-13, granite porphyry, 23 spots, weighted mean age = 231 ± 2.4 Ma, MSWD = 1.9																
L20617-13-01	64.45	792	1401	0.57	0.0509	0.0019	0.2544	0.0094	0.0358	0.0004	239	88.88	230	7.65	227	2.65
L20617-13-02	60.14	613	1322	0.46	0.0502	0.0025	0.2514	0.0098	0.0357	0.0005	211	116.65	228	7.91	226	2.87
L20617-13-03	72.1	1044	1539	0.68	0.0512	0.0019	0.2617	0.0097	0.0366	0.0005	250	89.8	236	7.82	232	3.11
L20617-13-06	86.17	1545	1787	0.87	0.0499	0.0016	0.2484	0.0078	0.0358	0.0004	191	74.06	225	6.37	227	2.5
L20617-13-07	74.82	899	1689	0.53	0.0501	0.0019	0.2576	0.009	0.0366	0.0005	198	90.73	233	7.24	232	3.13
L20617-13-08	98.93	1473	1974	0.75	0.0496	0.0017	0.2466	0.0081	0.0358	0.0004	176	79.62	224	6.62	227	2.4
L20617-13-09	76.28	1119	1561	0.72	0.0499	0.0016	0.2559	0.0084	0.0368	0.0004	191	71.29	231	6.78	233	2.44

Table 1. Cont.

Spots	Content (ppm)				Ratios						Age					
	Total Pb	²³² Th	²³⁸ U	Th/U	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ
L20617-13-10	78.11	1082	1617	0.67	0.0495	0.0017	0.2552	0.0088	0.0372	0.0005	169	84.25	231	7.1	235	2.93
L20617-13-11	51.49	583	1145	0.51	0.0502	0.0021	0.2472	0.0098	0.0356	0.0005	206	98.13	224	7.97	225	2.96
L20617-13-12	46.08	500	995	0.5	0.0502	0.0017	0.2558	0.0089	0.0368	0.0005	206	79.62	231	7.21	233	2.85
L20617-13-13	76.42	989	1603	0.62	0.0504	0.0015	0.2553	0.0079	0.0365	0.0004	213	72.21	231	6.37	231	2.4
L20617-13-14	35.82	321	774	0.41	0.0509	0.0018	0.2614	0.0094	0.0369	0.0004	235	81.47	236	7.53	234	2.57
L20617-13-15	53.56	520	1146	0.45	0.0497	0.002	0.2536	0.0085	0.0366	0.0004	189	94.43	229	6.9	232	2.58
L20617-13-16	61.1	635	1277	0.5	0.0498	0.0019	0.2574	0.0096	0.0372	0.0005	183	119.43	233	7.78	235	2.86
L20617-13-18	35.99	303	782	0.39	0.0519	0.0023	0.2665	0.0117	0.037	0.0005	280	106.47	240	9.39	234	3.35
L20617-13-19	77.43	930	1591	0.58	0.0506	0.0017	0.2615	0.0088	0.0371	0.0005	220	75.91	236	7.09	235	2.89
L20617-13-20	112.76	1800	2200	0.82	0.0507	0.0015	0.2618	0.008	0.0372	0.0004	233	70.36	236	6.42	236	2.71
L20617-13-22	105.11	1834	2133	0.86	0.0514	0.0014	0.2546	0.0069	0.0357	0.0004	261	61.1	230	5.6	226	2.54
L20617-13-23	53.53	562	1152	0.49	0.0505	0.0016	0.2587	0.0085	0.037	0.0004	217	80.54	234	6.83	234	2.64
L20617-13-24	31.08	308	704	0.44	0.05	0.0018	0.2484	0.0094	0.0358	0.0005	195	85.17	225	7.62	227	3.02
L20617-13-25	71.13	900	1381	0.65	0.0504	0.0033	0.2551	0.0182	0.0357	0.0004	213	149.98	231	14.69	226	2.72
L20617-13-26	96.29	1775	1937	0.92	0.0511	0.0019	0.2499	0.0085	0.0359	0.0006	256	80.54	227	6.94	227	3.6
L20617-13-27	47.77	510	1056	0.48	0.0511	0.0022	0.2542	0.0093	0.0358	0.0004	256	98.14	230	7.53	227	2.48

The granitoids had high silica contents and low MgO, FeOT contents and La/Yb, Sr/Yb ratios (Figure 8), suggesting that they were mainly derived from the partial melting of crustal materials. The isotopic data provided good constraints on the source of the Taijiying granite porphyries (Table 3). They had low initial ⁸⁷Sr/⁸⁶Sr ratios (0.7031 to 0.7078), concentrated ε_{Nd}(t) values (−1.2 to 1.7), positive zircon ε_{Hf}(t) values (+3.5 to +10.7, mean = +6.7), and relatively low δ¹⁸O values (6.29 to 7.84, mean = 6.85) (Figures 9 and 10), which indicate that mantle-derived material played a critical role. The positive ε_{Hf}(t) values also suggest that the Taijiying granite porphyries have not experienced extensive mixing of an ancient continental crust endmember. However, there was some reworking of ancient crustal material in the source based on the negative ε_{Nd}(t) values. The Taijiying rocks had similar T_{DM2} (0.87–1.09 Ga) and T_{DM^C} (0.58–1.04 Ga) ages, which indicate that the sources were derived from the depleted mantle and evolved into basaltic low crust during the Neoproterozoic. The basalts were altered by Archean seawater which increased the zircon δ¹⁸O values (Figure 10). The granitic magma rapidly ascended into shallow magma chambers by partial melting and finally formed the Taijiying granite porphyries. The plagioclase surrounding quartz phenocrysts indicate rapid emplacement and cooling of the magma (Figure 2d–f).

A previous study proposed that the Taijiying gold deposit is spatially and temporally related to these Triassic granite porphyries [7]. The magmatic hydrothermal fluids evolving from the granitic magmas provided not only metals and fluids but also the external heat to promote the gold-rich fluids upward, leading to the deposition with mixed features of the magmatic and meteoric fluids.

Table 2. Whole-rock geochemical data of granite porphyry in Taijiying.

Samples	L20617-1-1	L20617-2-1	L20617-3-1	L20617-4-1	L20617-5-1	L20617-7	L20617-8	L20617-9	L20617-10	L20617-11	L20617-12	L20617-13	L20617-14	L20617-15
<i>Major elements (wt.%)</i>														
SiO ₂	73.9	73.4	75.3	75.9	76.7	76.1	69.0	76.2	75.3	77.0	77.6	75.7	76.6	77.2
TiO ₂	0.12	0.11	0.11	0.11	0.09	0.10	0.10	0.10	0.11	0.10	0.10	0.11	0.10	0.10
Al ₂ O ₃	12.5	12.5	12.6	12.6	12.3	12.2	11.4	12.3	12.6	12.5	12.2	12.6	12.3	12.5
Fe ₂ O ₃	0.83	0.76	1.02	0.89	0.90	1.67	1.40	1.72	1.42	1.41	1.46	1.88	1.77	1.39
MnO	0.04	0.04	0.02	0.03	0.04	0.02	0.12	0.02	0.03	0.02	0.01	0.03	0.04	0.02
MgO	0.53	0.53	0.49	0.61	0.40	0.18	0.20	0.38	0.19	0.21	0.20	0.28	0.21	0.22
CaO	1.15	1.23	0.48	0.44	0.48	0.75	5.40	0.61	0.74	0.20	0.12	0.54	0.39	0.20
Na ₂ O	2.90	3.27	3.04	2.65	2.84	3.89	3.52	2.72	3.48	2.35	3.18	3.24	4.12	2.36
K ₂ O	4.55	4.96	4.30	4.25	4.67	4.04	3.92	4.15	4.19	4.63	4.44	4.56	3.82	4.58
P ₂ O ₅	0.02	0.01	0.01	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
LOI	2.09	1.80	1.50	0.96	1.07	1.12	4.93	1.58	1.32	1.19	0.83	1.28	0.91	1.28
Total	99.60	99.63	99.59	99.26	100.41	100.10	100.06	99.72	99.36	99.55	100.16	100.13	100.35	99.86
FeO	1.03	0.96	0.69	0.79	0.86	0.90	0.72	0.92	0.60	0.65	0.64	1.12	0.97	0.64
FeOT	1.78	1.64	1.61	1.59	1.67	2.41	1.98	2.46	1.88	1.92	1.95	2.81	2.56	1.89
Mg#	38.48	40.34	38.99	44.57	33.44	13.62	17.57	24.29	17.32	18.48	17.83	17.50	14.91	19.85
K ₂ O/Na ₂ O	1.57	1.52	1.41	1.60	1.64	1.04	1.11	1.53	1.20	1.97	1.40	1.41	0.93	1.94
A/CNK	1.06	0.96	1.20	1.29	1.16	1.01	0.58	1.22	1.09	1.35	1.19	1.12	1.06	1.36
Tzr	787	774	809	804	801	786	702	800	784	809	805	903	906	924
<i>Trace elements (ppm)</i>														
Li						3.16	3.94	12.2	4.97	8.61	4.08	3.67	1.97	3.63
Be						1.79	2.20	2.43	2.31	2.89	2.02	1.68	1.83	1.79
Sc						1.52	1.42	1.28	1.64	1.34	1.29	1.39	1.52	1.28
V	8.31	8.14	8.29	12.3	6.50	1.98	1.87	2.56	1.72	2.72	2.47	5.72	1.46	6.25
Cr	5.81	6.61	5.63	30.1	8.56	42.9	8.06	6.28	8.24	10.5	5.53	16.9	7.56	15.1
Co	0.86	0.67	0.61	2.16	0.89	0.62	0.64	0.66	0.35	0.31	0.32	0.41	0.38	0.40
Ni	4.13	4.33	4.00	14.7	5.55	2.76	1.94	12.0	1.56	1.54	1.73	2.19	1.90	2.36
Cu						4.93	3.03	4.42	2.77	3.32	2.80	3.58	3.94	3.72
Zn						29.6	22.3	25.3	26.3	38.6	28.2	36.0	32.2	36.7
Ga						16.7	16.6	17.8	19.1	20.4	16.5	17.5	17.1	17.4
Rb	167	179	178	225	246	128	137	145	164	193	160	171	142	168
Sr	43.7	57.9	51.3	50.9	41.9	44.0	127	39.0	46.3	18.2	34.9	48.5	40.5	48.4
Y	23.6	19.9	17.8	12.5	16.3	18.2	18.6	16.7	18.6	17.5	18.1	18.8	19.0	18.6
Zr	166	181	175	97.0	112	170	157	155	171	152	168	174	182	170
Nb	35.3	32.0	33.2	21.5	32.1	25.7	25.4	27.2	26.7	25.3	26.9	26.8	27.7	26.5
Sn	3.36	3.36	3.13	1.97	2.96	2.60	2.44	2.56	2.90	3.29	2.60	2.89	2.84	2.98
Cs						1.37	1.51	1.74	3.04	3.92	1.60	1.75	2.02	1.75
Ba	117.0	105.0	138.0	150.0	117.0	120	94.5	175	82.7	107	122	100.0	52.5	98.1
La	53.7	50.9	51.0	22.8	18.7	46.0	49.6	43.5	48.4	47.0	46.7	46.8	48.8	46.8
Ce	118	102	102	42.2	46.7	94.8	101	94.4	101	97.5	97.5	96.3	100	96.9
Pr	13.2	11.1	11.2	5.04	4.64	10.2	10.9	10.3	10.8	10.5	10.6	10.5	10.9	10.4

Table 2. Cont.

Samples	L20617-1-1	L20617-2-1	L20617-3-1	L20617-4-1	L20617-5-1	L20617-7	L20617-8	L20617-9	L20617-10	L20617-11	L20617-12	L20617-13	L20617-14	L20617-15
Nd	42.7	36.6	36.3	16.9	15.9	34.5	37.7	35.5	36.7	35.9	36.3	34.7	36.5	34.9
Sm	7.29	6.21	5.98	3.18	3.25	6.13	6.49	6.26	6.24	6.36	6.70	6.45	6.39	6.16
Eu	0.22	0.27	0.29	0.39	0.24	0.23	0.25	0.24	0.23	0.25	0.24	0.23	0.23	0.25
Gd	6.62	5.60	5.50	2.71	2.81	4.04	4.31	4.00	4.24	4.21	4.26	4.13	4.32	4.22
Tb	0.88	0.75	0.69	0.38	0.45	0.61	0.65	0.59	0.63	0.61	0.68	0.61	0.67	0.63
Dy	4.43	3.69	3.39	2.18	2.85	3.49	3.44	3.09	3.44	3.26	3.44	3.50	3.54	3.44
Ho	0.79	0.65	0.59	0.40	0.53	0.60	0.61	0.58	0.65	0.60	0.61	0.63	0.66	0.61
Er	2.48	2.06	1.94	1.26	1.64	1.75	1.77	1.54	1.80	1.59	1.69	1.78	1.75	1.67
Tm	0.37	0.30	0.28	0.20	0.28	0.25	0.25	0.24	0.26	0.25	0.25	0.25	0.26	0.26
Yb	2.43	2.06	1.89	1.37	1.78	1.63	1.62	1.59	1.70	1.68	1.63	1.70	1.69	1.67
Lu	0.40	0.33	0.29	0.22	0.29	0.24	0.23	0.23	0.25	0.24	0.25	0.25	0.25	0.25
Hf	4.42	4.56	4.44	2.40	3.06	5.49	4.92	5.12	5.49	5.21	5.33	5.62	5.57	5.59
Ta	2.86	2.83	2.86	2.30	2.82	2.06	1.95	2.16	2.19	2.10	2.13	2.02	2.15	2.01
Tl						0.79	0.88	0.95	1.07	1.14	1.09	1.06	0.91	1.08
Pb						10.9	7.79	6.77	9.03	7.18	10.3	11.8	10.5	11.5
Th	28.0	27.7	26.8	26.8	27.2	28.2	27.4	28.8	28.9	28.4	29.7	29.6	29.2	29.2
U	4.25	8.32	6.52	3.57	3.37	6.55	5.94	4.55	4.50	3.38	6.09	6.95	6.28	6.79
Th/U	6.58	3.32	4.10	7.51	8.06	4.30	4.62	6.33	6.42	8.39	4.87	4.26	4.66	4.30
Rb/Sr	3.82	3.10	3.46	4.42	5.88	2.92	1.08	3.73	3.55	10.63	4.57	3.52	3.50	3.48
Zr/Y	7.03	9.11	9.86	7.70	6.89	9.38	8.43	9.32	9.21	8.70	9.27	9.24	9.55	9.15
Sr/Y	1.85	2.91	2.88	4.07	2.57	2.42	6.82	2.34	2.49	1.04	1.93	2.58	2.13	2.61
ΣREE	253.62	222.28	221.31	99.28	100.09	204.44	218.76	202.06	216.38	209.95	210.89	207.89	216.40	208.11
LREE/HREE	12.79	13.40	14.21	10.38	8.43	15.22	15.97	16.04	15.68	15.88	15.48	15.19	15.47	15.34
La _N /Yb _N	15.8	17.7	19.4	11.9	7.6	20.3	22.0	19.6	20.4	20.0	20.6	19.8	20.8	20.1
δEu	0.10	0.14	0.15	0.40	0.24	0.14	0.14	0.14	0.14	0.15	0.14	0.14	0.13	0.15
δCe	1.06	1.00	1.00	0.92	1.19	1.07	1.07	1.09	1.08	1.08	1.07	1.06	1.07	1.08
⁸⁶ Rb/ ⁸⁶ Sr						8.672	4.815	12.647	12.437			11.543	12.801	
⁸⁷ Sr/ ⁸⁶ Sr						0.735249	0.720037	0.747575	0.748085			0.740880	0.749636	
2σ						8	6	9	9			10	10	
(⁸⁷ Sr/ ⁸⁶ Sr) _i						0.70688	0.70429	0.7062	0.7074			0.70312	0.70776	
¹⁴⁷ Sm/ ¹⁴⁴ Nd						0.1022	0.1976	0.1530	0.1079			0.1564	0.1840	
¹⁴³ Nd/ ¹⁴⁴ Nd						0.512582	0.51258	0.512588	0.512581			0.512583	0.512582	
2σ						5	5	5	7			5	5	
ε _{Nd} (t)						1.7	−1.2	0.37	1.5			0.12	−0.72	
T _{DM2}						870	1089	980	886			996	1060	
f _{Sm} /Nd						−0.48	−0.5	−0.48	−0.45			−0.51	−0.51	

Note: Mg# = (MgO/40.31)/(MgO/40.31 + FeOT/71.85 × 0.85) × 100; FeOT = FeO + 0.8998 × Fe₂O₃.

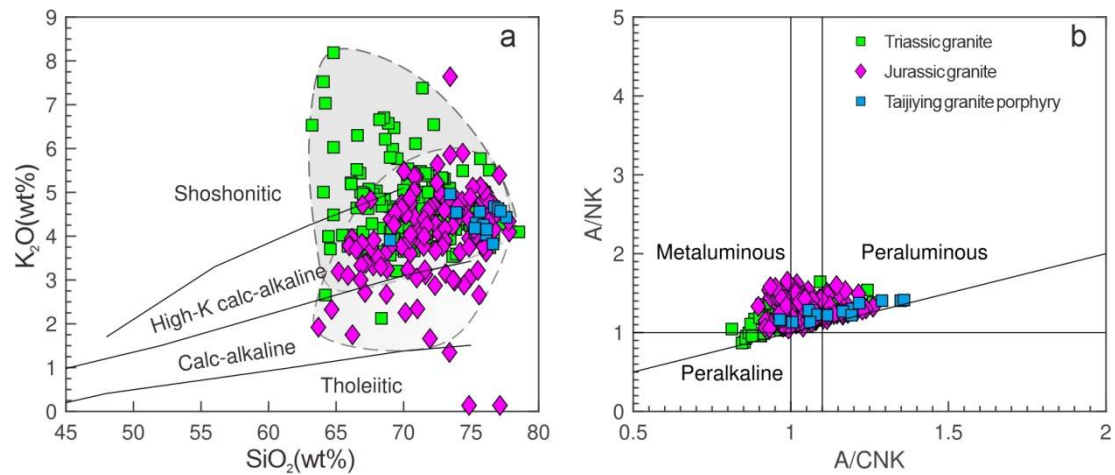


Figure 4. (a) Plots of K₂O vs. SiO₂ diagram; (b) A/NK (molar ratio Al₂O₃/(Na₂O + K₂O)) vs. A/CNK (molar ratio Al₂O₃/(CaO + Na₂O + K₂O)) diagram for granite porphyries from Chifeng–Chaoyang district ((a) is based on [37]).

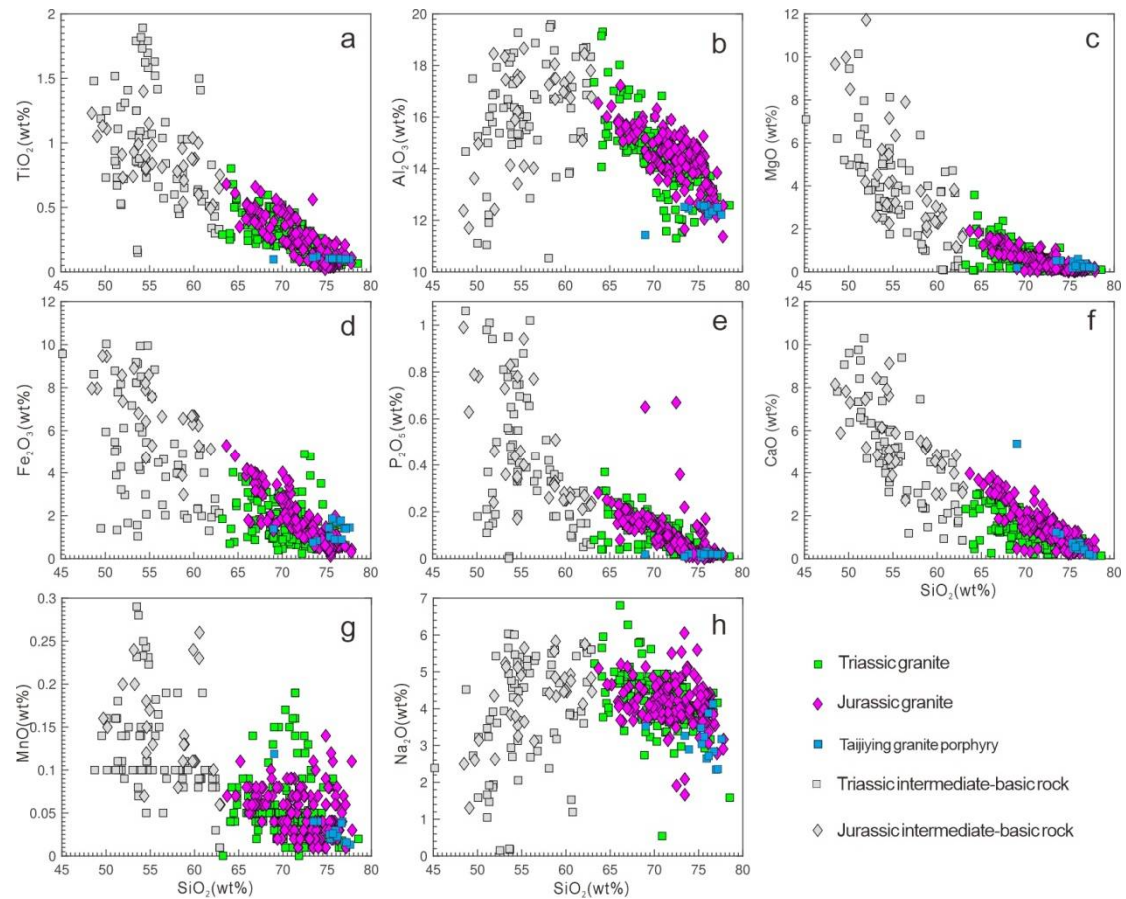


Figure 5. Harker diagrams for Chifeng–Chaoyang granites. (a) TiO₂ vs. SiO₂; (b) Al₂O₃ vs. SiO₂; (c) MgO vs. SiO₂; (d) Fe₂O₃ vs. SiO₂; (e) P₂O₅ vs. SiO₂; (f) CaO vs. SiO₂; (g) MnO vs. SiO₂; (h) Na₂O vs. SiO₂.

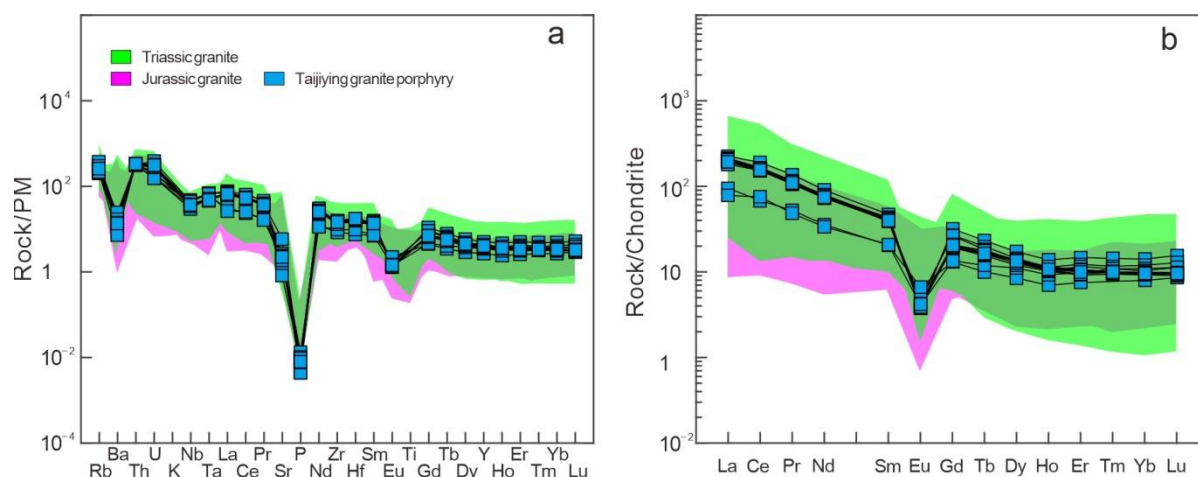


Figure 6. (a) Primitive, mantle-normalized trace element diagram for granite; (b) chondrite-normalized REE patterns diagram for granites. The chondrite values are from [38]. The primitive mantle values are from [39].

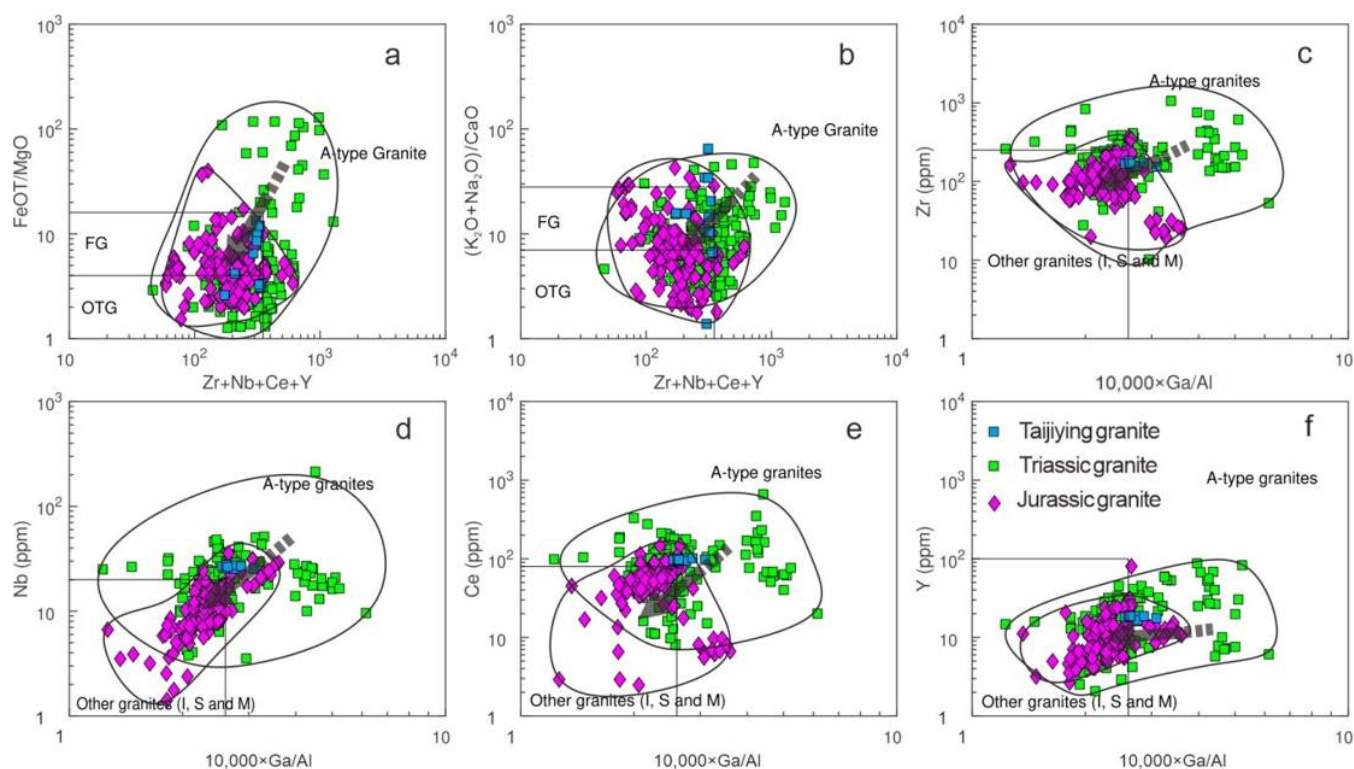


Figure 7. Classification diagrams for the Triassic and Jurassic granitic rocks. (a) FeOT/MgO vs. $(Zr + Nb + Ce + Y)$, (b) $(K_2O + Na_2O)/CaO$ vs. $(Zr + Nb + Ce + Y)$, (c) Zr vs. $10,000 Ga/Al$, (d) Nb vs. $10,000 Ga/Al$, (e) Ce vs. $10,000 Ga/Al$, and (f) Y vs. $10,000 Ga/Al$ classification diagrams [40], indicating that the Triassic granites are transitional between the I-, S-, M-, and A-types or highly fractionated, and Jurassic granites are mainly the I-, S-, M-, or unfractionated types, with few A-types or highly fractionated granites. A: A-type granite; I, S, and M: I-, S-, and M-type granite; FG: fractionated felsic granite; OTG: unfractionated M-, I-, and S-type granite.

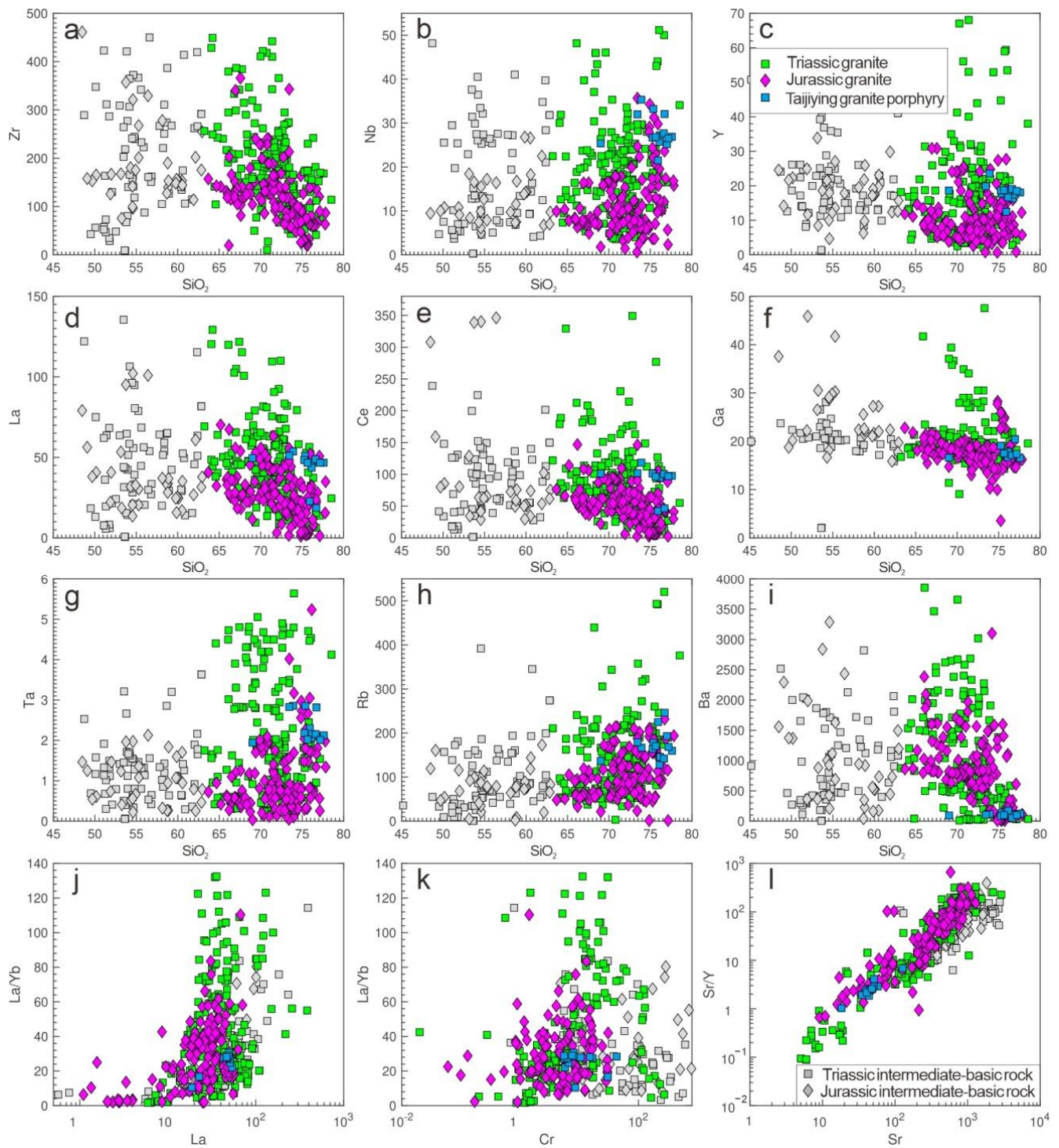


Figure 8. Elemental variation diagrams for Chifeng–Chaoyang district granites. (a) Zr vs. SiO_2 ; (b) Nb vs. SiO_2 ; (c) Y vs. SiO_2 ; (d) La vs. SiO_2 ; (e) Ce vs. SiO_2 ; (f) Ga vs. SiO_2 ; (g) Ta vs. SiO_2 ; (h) Rb vs. SiO_2 ; (i) Ba vs. SiO_2 ; (j) La/Yb vs. La; (k) La/Yb vs. Cr; (l) Sr/Y vs. Sr.

Table 3. Hf–O isotopic compositions of zircons from the granite porphyry samples of the Taijiying gold deposit, western Liaoning.

No.	Age (Ma)	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	2σ	$\varepsilon_{\text{Hf}}(0)$	$\varepsilon_{\text{Hf}}(t)$	T_{DM}	T_{DM}^c	$f_{\text{Lu/Hf}}$	$\delta^{18}\text{O}$ (‰)	$\pm 2\sigma$
L20617-9-01	234	0.055540	0.001231	0.282824	0.000035	1.82	6.78	610	831	−0.96	6.69	0.15
L20617-9-02	234	0.088477	0.001983	0.282748	0.000035	−0.86	3.98	733	1011	−0.94	6.64	0.18
L20617-9-03	234	0.086536	0.001867	0.282834	0.000037	2.18	7.02	606	815	−0.94	6.73	0.13
L20617-9-04	234	0.101975	0.002190	0.282839	0.000034	2.38	7.20	603	805	−0.93	6.53	0.17
L20617-9-05	234	0.093398	0.001997	0.282854	0.000032	2.89	7.73	579	771	−0.94	6.77	0.26
L20617-9-06	234	0.068455	0.001532	0.282799	0.000034	0.94	5.86	651	891	−0.95	6.79	0.17
L20617-9-07	234	0.064702	0.001563	0.282820	0.000033	1.68	6.60	621	843	−0.95	6.76	0.19
L20617-9-08	234	0.047334	0.001183	0.282765	0.000029	−0.24	4.72	693	964	−0.96	6.96	0.07
L20617-9-09	234	0.056710	0.001461	0.282778	0.000034	0.21	5.15	679	936	−0.96	6.41	0.12
L20617-9-10	234	0.091339	0.002086	0.282878	0.000030	3.73	8.55	546	718	−0.94	6.55	0.23
L20617-9-11	234	0.074405	0.001791	0.282834	0.000035	2.20	7.09	604	813	−0.95	6.29	0.17
L20617-9-12	234	0.075216	0.001717	0.282837	0.000032	2.28	7.17	600	808	−0.95	6.87	0.14
L20617-9-13	234	0.056767	0.001338	0.282772	0.000035	−0.01	4.94	686	950	−0.96	6.44	0.20
L20617-9-14	234	0.050499	0.001185	0.282802	0.000029	1.07	6.03	640	880	−0.96	6.67	0.14
L20617-9-15	234	0.074764	0.001710	0.282915	0.000035	5.06	9.96	486	629	−0.95	6.71	0.21
L20617-13-01	230	0.074041	0.001555	0.282828	0.000030	1.97	6.79	610	828	−0.95	6.85	0.14
L20617-13-02	230	0.109095	0.002230	0.282816	0.000034	1.56	6.30	638	861	−0.93	7.49	0.12
L20617-13-03	230	0.093436	0.001965	0.282899	0.000032	4.49	9.27	513	671	−0.94	7.54	0.16
L20617-13-04	230	0.061286	0.001349	0.282798	0.000032	0.92	5.77	649	893	−0.96	6.53	0.17
L20617-13-05	230	0.112168	0.002389	0.282877	0.000030	3.71	8.42	551	724	−0.93	7.84	0.18
L20617-13-06	230	0.106823	0.002312	0.282941	0.000036	5.97	10.69	457	580	−0.93	7.51	0.20
L20617-13-07	230	0.098713	0.002224	0.282785	0.000035	0.47	5.20	683	930	−0.93	7.03	0.25
L20617-13-08	230	0.068805	0.001689	0.282810	0.000031	1.34	6.16	637	869	−0.95	6.76	0.12
L20617-13-09	230	0.059943	0.001473	0.282866	0.000032	3.32	8.17	554	741	−0.96	7.67	0.20
L20617-13-10	230	0.062086	0.001544	0.282734	0.000044	−1.35	3.47	744	1040	−0.95	6.93	0.21
L20617-13-11	230	0.078422	0.001752	0.282831	0.000034	2.07	6.86	609	824	−0.95	6.79	0.26
L20617-13-12	230	0.071436	0.001551	0.282826	0.000033	1.91	6.72	612	832	−0.95	6.59	0.16
L20617-13-13	230	0.050549	0.001240	0.282811	0.000034	1.39	6.26	628	862	−0.96	6.95	0.11
L20617-13-14	230	0.071913	0.001660	0.282803	0.000035	1.10	5.91	647	885	−0.95	6.86	0.31
L20617-13-15	230	0.058868	0.001305	0.282798	0.000033	0.93	5.80	648	893	−0.96	6.39	0.13

Note: $\varepsilon_{\text{Hf}}(t) = 10,000 \times \{[(^{176}\text{Hf}/^{177}\text{Hf})_{\text{S}} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{S}} \times (e^{\lambda t} - 1)] / [(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR},0} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} \times (e^{\lambda t} - 1)] - 1\}$; $T_{\text{DM}} = 1/\lambda \times \ln\{1 + [(^{176}\text{Hf}/^{177}\text{Hf})_{\text{S}} - (^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}}] / [(^{176}\text{Lu}/^{177}\text{Hf})_{\text{S}} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}}]\}$; $T_{\text{DM}}^c = T_{\text{DM}1} - (T_{\text{DM}1} - t) \times [(f_{\text{cc}} - f_{\text{s}}) / (f_{\text{cc}} - f_{\text{DM}})]$, $f_{\text{Lu/Hf}} = (^{176}\text{Lu}/^{177}\text{Hf})_{\text{S}} / (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR} - 1}$, where $\lambda = 1.867 \times 10^{-11} \text{ year}^{-1}$ (Soderlund et al., 2004); $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{S}}$ and $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{S}}$ are the measured values of the samples; $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} = 0.0332$ and $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR},0} = 0.282772$ (Blichert-Toft and Albarede, 1997); $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}} = 0.0384$ and $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}} = 0.28325$ (Griffin et al., 2000); $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{mean crust}} = 0.015$; $f_{\text{cc}} = [(^{176}\text{Lu}/^{177}\text{Hf})_{\text{mean crust}} / (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}}] - 1$; $f_{\text{s}} = f_{\text{Lu/Hf}}$; $f_{\text{DM}} = [(^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}} / (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}}] - 1$; t = crystallization time of zircon.

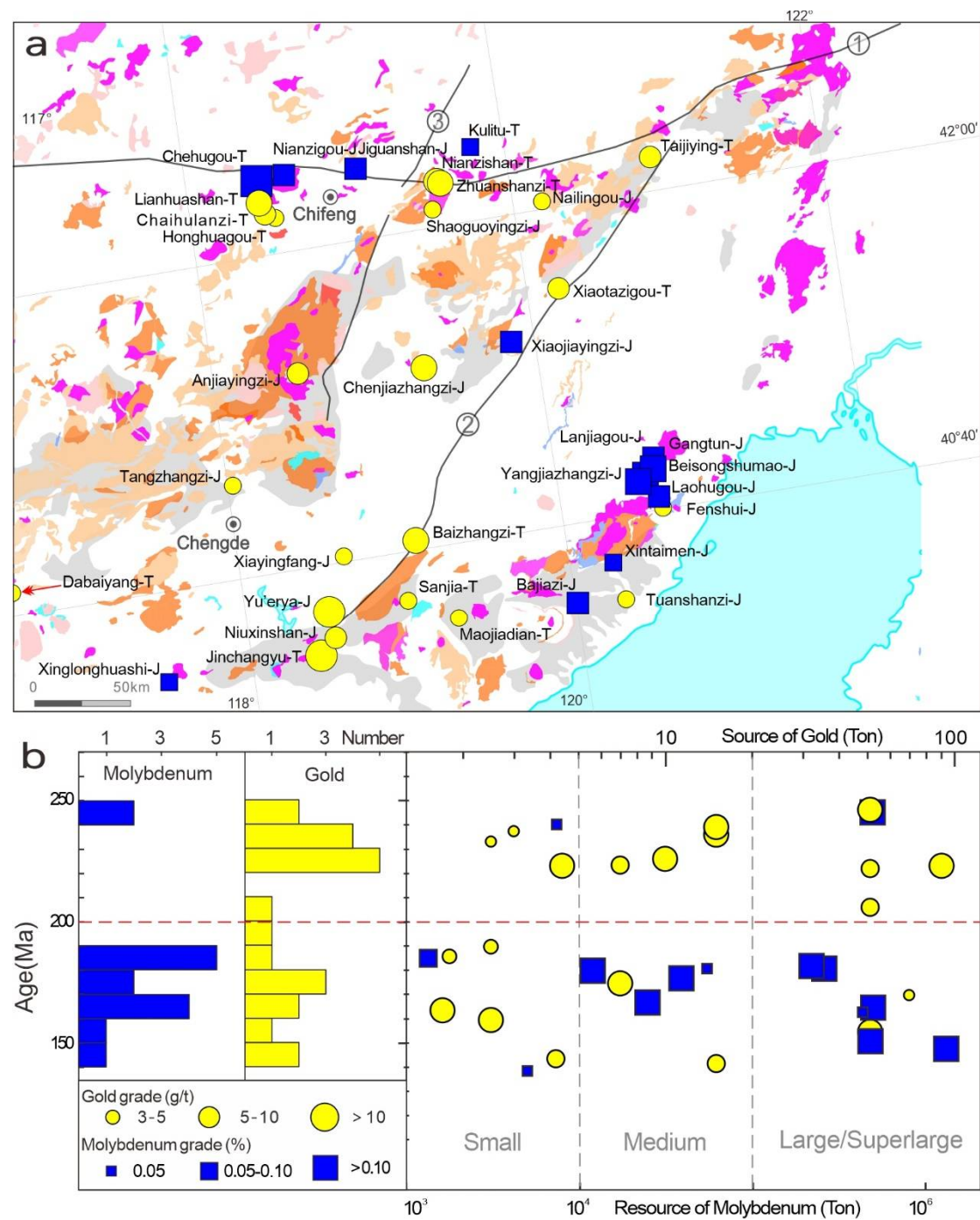


Figure 9. (a) Outline map of the Chifeng–Chaoyang district showing distribution of the Mesozoic gold and molybdenum deposits. ①—Chifeng–Kaiyuan fault; ②—Lingyuan–Beipiao fault; ③—Honghan–Balihan fault; (b) The periodical pattern of Triassic and Jurassic gold and molybdenum deposits.

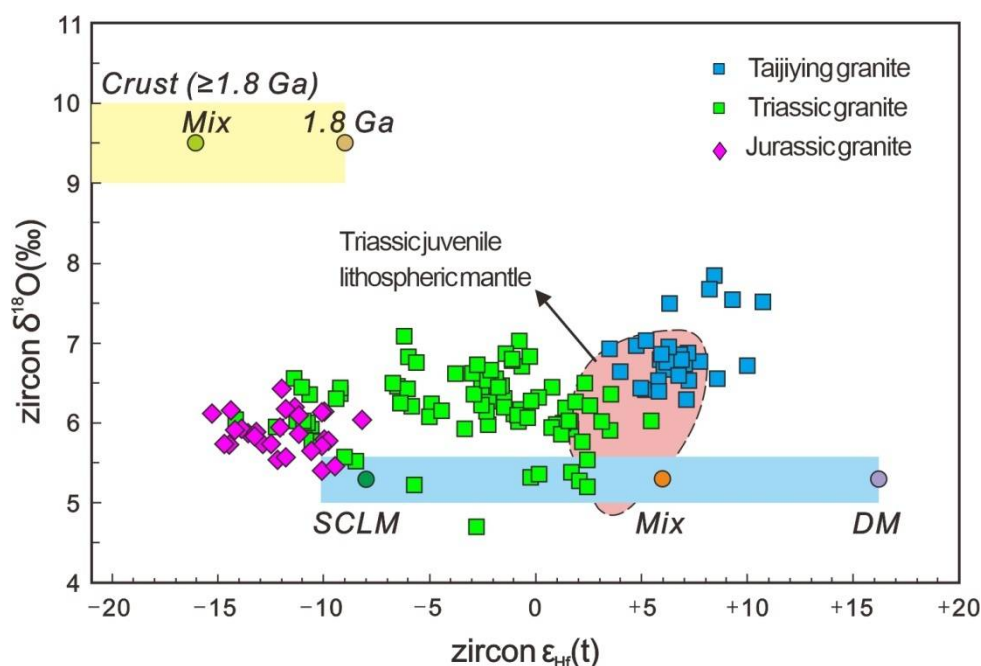


Figure 10. Zircon $\delta^{18}\text{O}$ versus $\epsilon_{\text{Hf}}(t)$ of Triassic granite porphyries in Taijiying gold deposit. The $\epsilon_{\text{Hf}}(t)$ values of depleted mantle, the SCLM beneath the NCC, mixed mantle, and ancient crust are +16.2, −8 [33], +6, and −16, respectively. The $\delta^{18}\text{O}$ of ancient crust and mantle are $+9.5 \pm 0.5\%$ (average of 2.5 Ga and 1.8 Ga crust) and $+5.3 \pm 0.3\%$ [41]. Age for calculation depends on the samples. Triassic spots from [8]. Jurassic spots from [42]. Triassic juvenile lithospheric mantles are from [33].

4. Geochemical Characteristics of Triassic and Jurassic Granitoids

The Chifeng–Chaoyang district includes Kalaqin, Lunu'erhu, Haitangshan–Yiwulushan, Xingcheng, and Dushan in the northeastern NCC, which produced large volumes of Triassic and Jurassic intrusions. The metals and fluids of orogenic gold deposits and porphyry molybdenum deposits all came from felsic magma which became granites. There are close relationships between granites and deposits. This paper compiles the data from the published literature for 208 Triassic–Jurassic granitoids related to these deposits (Supplementary Table S1). The data set contains whole-rock major and trace elements for 352 samples, Sr–Nd isotopic data for 113 samples, zircon Hf isotopic data for 36 samples (709 points), and O isotopic data for 10 samples (147 points). These data are presented in Supplementary Tables S2 and S3.

4.1. Triassic Granitoids

The compiled data for the Triassic granitic rocks exhibit a wide range of major element concentrations. They have high SiO_2 (63.2–78.6 wt%) and Al_2O_3 (11.3–19.3 wt%) contents and low MgO (0.03–2.62 wt%), Fe_2O_3 (0.24–4.88 wt%), CaO (0.14–3.05 wt%), Na_2O (0.54–6.80 wt%), K_2O (2.13–8.18 wt%), and $\text{Na}_2\text{O}/\text{K}_2\text{O}$ (mean value = 0.9, mostly < 1) contents. They all have low $\text{Mg\#}$, with a mean value of 32.26. Most samples are high-K calc-alkaline series with a small portion plotted in the shoshonitic field in the SiO_2 vs. K_2O classification diagram (Figure 4a) [43]. Most samples are metaluminous or weakly peraluminous in the A/NK vs. A/CNK diagram (Figure 4b). In the Harker diagrams, TiO_2 , Al_2O_3 , MgO , Fe_2O_3 , P_2O_5 , and CaO decrease with increasing SiO_2 , but MnO and Na_2O exhibit ambiguous correlations with SiO_2 (Figure 5).

The Triassic granites exhibit low Sr/Y ratios (mean = 53.7) and Sr contents (mean = 402 ppm) (Supplementary Table S2). They are characterized by high La/Yb ratios (1.6–132.5) and Nb (3.56–213 ppm), Cr (0.02–271 ppm), Y (2.07–87.0 ppm), Zr (10.17–1060 ppm), and Th (0.90–1233 ppm) contents. In the diagrams (Figure 8), the Sr, Zr, and Ba contents tend to decrease with increasing SiO_2 , while the Nb and Y contents are not correlated with SiO_2 .

The Triassic granitoids have variable total rare earth element (REE) contents, ranging from 34.0 to 1048 ppm (mean = 195). The Kalaqin batholiths monzogranite (06JH47R) has the highest REE values [8]. Except for a few samples with positive Eu anomalies ($\delta\text{Eu} = 3.37\text{--}1.00$; e.g., Dushan, Nanhouding, and Hekanzi) [32,44], they mainly exhibit slight-to-strong LREE enrichment ($\text{La}_\text{N}/\text{Yb}_\text{N} = 1.1\text{--}95.1$) in chondrite-normalized REE patterns and have significant, negative Eu anomalies with δEu values of 0.04–0.99 (mean = 0.72) (Figure 6b). In the primitive, mantle-normalized diagrams (Figure 6a), most of the samples, including the Taijiying granite porphyry, exhibit Ba, Sr, Nb, Ta, P, and Ti depletions and Th and U enrichments.

According to their relatively high Zr, Nb, Y, La, Ce, and Ga contents (Figure 8a–f), the majority of the Triassic samples are likely A-type granites. In the FeOT/MgO and $(\text{K}_2\text{O} + \text{Na}_2\text{O})/\text{CaO}$ vs. $(\text{Zr} + \text{Nb} + \text{Ce} + \text{Y})$ diagrams (Figure 7a,b), most of the Triassic samples are plotted in the A-type granite field or near the boundary between the A-type and fractionated/unfractionated granite fields. Furthermore, the $\text{K}_2\text{O} + \text{Na}_2\text{O}$, molecular $[\text{K}_2\text{O} + \text{Na}_2\text{O}]/\text{Al}_2\text{O}_3$, Nb, and Zr vs. 10,000 Ga/Al classification diagrams also show that the samples straddle the transitional fields between A-type and M-, I-, and S-type granites (Figure 7c–f) [45]. Therefore, the Triassic granites consist of both I-type and A-type granites.

4.2. Jurassic Granitoids

Compared to the Triassic granitoids, the Jurassic samples exhibited similar SiO_2 contents (63.7–77.8 wt%), a wide Al_2O_3 range (11.4–17.2 wt%), high CaO contents (0.22–3.97 wt%), and low $\text{Fe}_2\text{O}_3\text{T}$ (0.12–5.28 wt%), MgO (0.02–1.92 wt%), and $\text{Na}_2\text{O} + \text{K}_2\text{O}$ (0.27–5.70 wt%) contents. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios ranged from 0.3 to 5.7 (mostly > 1) (Supplementary Table S2). According to Peccerillo and Taylor's (1976) classification, most of the samples were the high-K calc-alkaline series [44]. A few of the granites were calc-alkaline granites (Figure 4a), which are different from the Triassic granites. In the A/NK vs. A/CNK diagram (Figure 4b), more Jurassic samples exhibit peraluminous characteristics than Triassic samples. In the Harker diagrams (Figure 5), TiO_2 , Al_2O_3 , MgO, $\text{Fe}_2\text{O}_3\text{T}$, CaO, and P_2O_5 decrease with increasing SiO_2 . The correlation between P_2O_5 and SiO_2 indicates that the Jurassic granites are not S-type granites. The Jurassic plutons also exhibited low and variable total REE contents, ranging from 6.46 to 375 ppm (mean = 122 ppm). Compared to the others, the samples from Yiwulüshan and Gaoliduntai had extremely low total REE contents, ranging from 6.46 to 20.4 ppm [40,44,46]. They had similar chondrite-normalized REE patterns and moderate LREE enrichment, with $\text{La}_\text{N}/\text{Yb}_\text{N}$ ratios of 1.5 to 79.1 (mean = 19.7) and variable Eu anomalies (0.04–4.63, mostly = 0.80–1.00) (Figure 6b).

The Jurassic granitoids have relatively high Sr/Y ratios (0.7–665.5) and lower La/Yb ratios (2.1–110.3) (Figure 8j–l). They are characterized by low Nb (0.65–88 ppm), Ta (0.03–10.4 ppm), Zr (19.4–366 ppm), Y (0.75–225 ppm), and Cr (0.06–30.5 ppm) contents (Supplementary Table S2). In the primitive, mantle-normalized diagrams (Figure 6a), most of the samples are depleted in Ba, Nb, Sr, P, Zr, and Ti and enriched in U, Th, and Nd. In Figure 7, most samples are plotted in the I-type granite field, which indicates that they do not have the distinctive features of A-type granites. However, some of the granites emplaced in the Xingcheng, Dushan, and Haitangshan MCCs have high $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios (>1), Sr contents (>400 ppm), and Sr/Y (>20.0–40.0) and La/Yb (>7.6–15.0) ratios. These granitoids also have low Y (<18 ppm) and Yb (<1.9 ppm) contents and weak Eu anomalies. These geochemical features indicate that they are adakitic granites [47]. Based on the lithologies and geochemical features, most of the Jurassic granitoids belong to I-type granites with a little portion of adakitic granites [40].

5. Characteristics of Sr–Nd–Hf–O Isotopes

5.1. Sr–Nd Isotope

Whole-rock Sr–Nd isotopes and zircon Hf are important tools for tracing the evolution of the lithosphere and crust [48]. $T_{\text{DM}2}$ and T_{DM}^{C} are used to restrict when the magmatic source is derived from the depleted mantle [49].

The Sr and Nd isotope ratios of Triassic to Jurassic granitoids in the study area are listed in Supplementary Table S2. For all collected samples from the northern NCC, the $\epsilon_{\text{Nd}}(t)$ values exhibited a wide range from -17.2 to 0.65 (mean = -8.5), and the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios had relatively low values (0.7010 – 0.7098 , mostly = 0.7050), excluding the extremely low values of 0.6840 and 0.6992 of the Kalaqin batholiths [8] and Hekanzi syenite [32]. The Nd model ages (T_{DM}) plutons were 1.02 – 2.02 Ga with a mean value of 1.47 Ga.

The Jurassic granitoids are characterized by strongly negative $\epsilon_{\text{Nd}}(t)$ values from -24.9 to -3.8 (mostly < -15.0) and a wide range of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from 0.7032 to 0.7215 (mean value = 0.7076). Although there were several plutons with a younger age (T_{DM}) in the region, such as Dayingzi (0.87 – 0.90 Ga) and Nianzigou (0.75 – 0.90 Ga) [44], contrasting with Triassic ones, these Jurassic intrusions had much older ages (T_{DM}), from 1.31 Ga to 2.96 Ga (mean age = 2.17 Ga) (Supplementary Table S2).

5.2. Zircon Hf–O Isotope

The compiled Triassic granitoids zircon Hf isotopes are characterized by relatively low $^{176}\text{Hf}/^{177}\text{Hf}$ ratios (0.281702 to 0.282933), $\epsilon_{\text{Hf}}(t)$ values (-33.1 to 10.2 , mean value = -5.6), and older Hf isotopic crustal model ages (T_{DM}^{C}), 0.60 – 3.32 Ga (mean = 1.57 Ga). The $\delta^{18}\text{O}$ values varied from 4.69‰ to 7.84‰ (mean = 6.44‰). The zircon Hf isotopes of the Jurassic granitoids exhibited the lowest $^{176}\text{Hf}/^{177}\text{Hf}$ ratios, from 0.281193 to 0.282801 , $\epsilon_{\text{Hf}}(t)$ values of -34.5 to 4.7 (mostly = -12.8), and T_{DM}^{C} of 0.94 Ga to 3.36 Ga (mean = 2.11 Ga), respectively. The $\delta^{18}\text{O}$ values varied from 5.40‰ to 6.70‰ (mean = 5.96‰) (Supplementary Table S3). The $\epsilon_{\text{Hf}}(t)$ values gradually decreased with the ages when the T_{DM}^{C} aged from Triassic to Jurassic (Figures 10 and 11c). These features indicate that the Jurassic granitic sources had more Precambrian basement rocks involved in the process. The high $\delta^{18}\text{O}$ values of Triassic granites may be the result of basalts altered by Archean seawater [50,51].

6. Age and Types of Metallic Metallogeny

The gold and molybdenum mineralization represents the primary metallogeny in this district. More than 100 gold deposits have been discovered, which were produced in Meso-Neoproterozoic metamorphic rocks or Mesozoic intrusions. The large–medium gold deposits are found in Chaihuilanzhi, Honghuagou, Anjiayingzi, Zhuanshanzi, and Xiaotazigou, from west to east. The superlarge/large molybdenum deposits are distributed near the Xingcheng area and Chifeng City, which includes Lanjiagou, Yangjiazhangzi, Xintaimen and Chehugou [52–54]. The specific information can be seen in Supplementary Table S4.

It seems to be a pattern that gold mineralization mainly took place during the Triassic, and molybdenum deposits concentrated in the Jurassic. There were two peaks of gold mineralization in the Triassic and Jurassic: 250 – 230 Ma and 160 – 180 Ma (Figure 9). Triassic gold deposits are characterized by a higher grade and larger scale than those from the Jurassic. Twelve Triassic gold deposits exhibit high grade (ca. 5 – 30 g/t, mostly > 10 g/t) and large reserve scales (mostly > 5 t). For instance, the Jinchangyu orogenic gold deposit has 90 tonnes of gold reserves with a high grade of 14.6 g/t [55]. In contrast, Jurassic gold deposits are relatively small in reserve scale and lower in grade, which indicates that more intensive gold mineralization occurred in the Triassic. On the other hand, this study area is also called the Yan–Liao Mo belt and is one of the six Mo mineralization provinces in China [56]. Most large Mo deposits at the northern margins of the NCC are related to continental collision orogeny, including syn-collision to post-collision tectonism [56]. Wang et al. (2014) reported large–medium Mo polymetallic deposits in China mostly produced during 180 – 100 Ma and a few of deposits from the Indosinian [57]. In this area, Triassic Mo mineralization is represented by just one small-scale Kulitu and the superlarge-scale Chehugou deposits with a grade of 0.09% and 0.14% , respectively, along the north side of the Chifeng–Kaiyuan fault [58,59]. In contrast, Jurassic Mo mineralization is characterized by more deposits, larger reserve scale, and higher ore grade (Figure 9 and Supplementary Table S4). For example, the porphyry-type Lanjiagou (182 ± 7 Ma) Mo deposit has been estimated to be a reserve of molybdenum metal measuring more than 404,000 tons with an

average grade of 0.13% Mo [52]. The skarn-type Yangjiazhangzi Mo deposit (181 ± 1 Ma) near the Lanjiagou deposit contains 261,800 tons of Mo with an average grade of 0.14% [54]. To the north, the Xiaojiayingzi Mo (Fe) deposit, formed in 166 ± 5 Ma, shows the features of high-grade Mo (0.29%) and is large in scale (105,000 tons) [57]. The Nianzigou Mo deposit is a quartz-vein-type Mo deposit which has 25,000 tons of Mo with an average grade of 0.31%, ranking as a middle-sized deposit [59]. The host rock porphyritic monzogranite and its associated Mo mineralization occurred at 153 ± 5 Ma [60]. The Sr–Nd isotopic compositions and Re contents in molybdenite suggest a crust-dominated source, with a minor contribution from the mantle [61]. The geochemical features of the Chehugou Mo deposit also suggest that the ore-related granitoids were derived from ancient, garnet-bearing crustal rocks related to subduction of the Palaeo-Asian Ocean and subsequent continent–continent collision between the NCC and Siberian plates. It indicates that the mineralization intensities of gold and molybdenum were different in the different periods, i.e., most gold was deposited in the Triassic, while molybdenum deposits mainly took place in the Jurassic.

7. Discussion

7.1. Transition of the Granitoid Sources from the Triassic to the Jurassic

The Triassic granitoids in the northern part of the NCC mainly consist of leucogranite, monzogranite, biotite granite, and syenogranite [52]. They belong to I-type or A-type granites, which have relatively high SiO_2 , K_2O , and $\text{K}_2\text{O} + \text{Na}_2\text{O}$, low Sr contents and Mg# values, strong LREE enrichments, negative δEu values, and Ba, Nb, Ta, Sr, P, and Ti depletions. The sources are most likely to be the partial melting of crustal materials. The compiled Triassic granites had much lower negative $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ values and older Nd and Hf model ages ($T_{\text{DM}2}$ and T_{DM}^{C}). In the $\epsilon_{\text{Nd}}(t)$ vs. $(^{87}\text{Sr}/^{86}\text{Sr})_i$ diagram (Figure 11a), a portion of the granitoids overlap with or are plotted above the Ordovician kimberlites and mantle xenoliths in the eastern part of the NCC. Most of the samples plotted in the area are between the Ordovician kimberlites, the mantle xenoliths, and the Precambrian basement rocks of the NCC, but they are much closer to the former. This scenario indicates that the initial magma sources are mainly derived from the lithospheric mantle materials, mixed with a portion of ancient crustal components. Furthermore, the granitoids exhibit the same distribution pattern as the Triassic intermediate mafic rocks, which also support this conclusion. The $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ vs. crystallization age plots also indicate similar source features (Figure 11b,c).

The proposed mantle sources of the Triassic granitoids are also supported by many previous studies, including those on Guangtoushan alkaline granite [30], the Jianping monzogranite and syenogranite [62], the Ping’andi ferroan granitoid [15], and the Jinchanggouliang shoshonitic dikes [63]. The Triassic Jianping granites (237 Ma) exhibit $\epsilon_{\text{Nd}}(t)$ values of -10.6 to -9.1 and higher $(^{87}\text{Sr}/^{86}\text{Sr})_i$ values, which may indicate more assimilation of crustal materials. The Late Triassic Guangtoushan alkaline–peralkaline granites (220 ± 1 Ma, $\epsilon_{\text{Nd}}(t) = -9.9$ to -8.6) are considered to have been derived from the enriched sub-continental lithospheric mantle [30]. The integrated geological evidence suggests that the Jinchanggouliang shoshonitic dikes were derived from the mixing of the lower crust, the lithospheric mantle of the NCC, and the ascending asthenospheric melt in a post-orogenic extensional geodynamic setting [64]. To the west, the granitoids of the Kalaqin batholith are the products of the mixing of melts that were mainly derived from three end-member sources, the ≥ 1.8 Ga ancient crust, the lithospheric mantle beneath the NCC, and a likely juvenile endmember formed by the mixing of melts from the lithospheric mantle and depleted mantle. The possible percentage of the crustal and mantle sources based on zircon Hf–O isotopes is 10%–40% ancient-crust-derived magma [8]. In addition, a more juvenile endmember or lithospheric mantle played a major role [30]. The Baizhangzi adakitic granites (233 Ma) were derived from the lower continental crust that was modified by basaltic underplating during the early Mesozoic, which led to the formation of juvenile crustal materials [27]. The sources of the A-type granites are mainly juvenile, mantle-

derived components and a small portion of recycled ancient crust. Generally, regardless of the specific types of Triassic intrusive, the mixing of juvenile crustal melts derived from the lithospheric mantle and the depleted mantle was likely the major source. The few percentages of ancient crust materials led to $(^{87}\text{Sr}/^{86}\text{Sr})_i$ values increasing in a narrow range compared to the percentages of Precambrian basement rocks (Figure 11a).

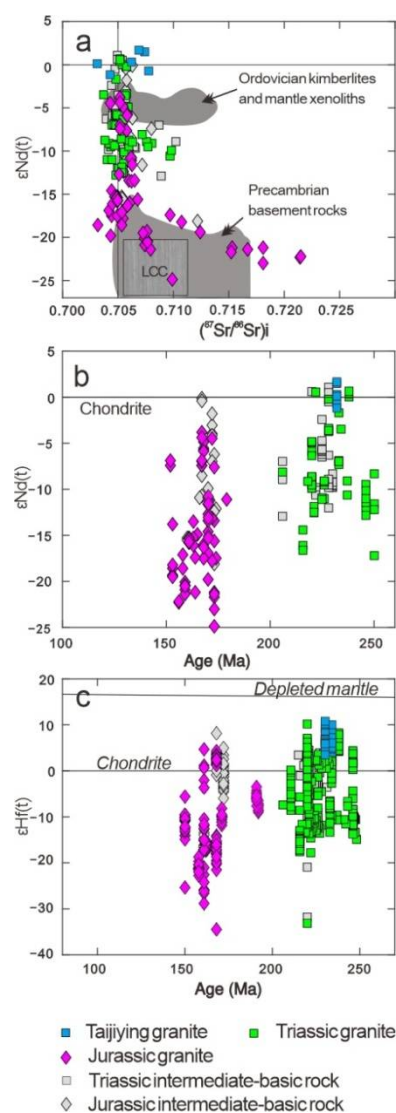


Figure 11. (a) Whole-rock $\epsilon\text{Nd}(t)$ vs. $(^{87}\text{Sr}/^{86}\text{Sr})_i$; (b) $\epsilon\text{Nd}(t)$ vs. age (Ma) diagram; (c) $\epsilon\text{Hf}(t)$ vs. age (Ma) diagram. Sr–Nd isotopic compositions of the Precambrian basement rocks in northern North China Craton (calculated at 310 Ma) are from [18,65], and those of the Ordovician kimberlites and mantle xenoliths (calculated at 310 Ma) in eastern North China Craton are from [63,66]. The compositions of the lower continental crust (LCC) based on [67] are also plotted.

Jurassic magmatic rocks mainly consist of granite, monzogranite with minor leucogranite, granodiorite, gabbro, lamprophyre, tonalite, and mafic microgranular enclaves (MMEs). Most of the Jurassic intrusive rocks are high-K calc-alkaline or calc-alkaline (Figure 4a). The intrusive rocks are mostly characterized by LREE enrichment, small negative or positive Eu anomalies, high Al_2O_3 , Na_2O , $\text{Na}_2\text{O}/\text{K}_2\text{O}$, Sr, and Ba contents, and low MgO , Y, Yb, and HFSE (Nb, Ta, Zr, Hf) contents. Their adakitic features suggest that olivine and plagioclase were not residual phases in the source region, but garnet, amphibole, and pyroxene were [68]. The Jurassic plutons mostly exhibited Ba, Nb, Sr, P, Zr, and Ti depletions and U, Th, and Nd enrichments, indicating a source containing residual eclogite. The Nd/Th

ratios (mean = 3.3) and Ti/Zr ratios (mean = 12.4) were closer to the values of 3 and <30 for continental crust, respectively, indicating that the genesis of granitoids also involved crustal melting. The partial melting of the thickened lower crust has been reported to be the main source of some Jurassic intrusive rocks [68–70]. The Archean–Paleoproterozoic inherited ~2.5 Ga zircons, also indicating the involvement of compositions of more ancient crustal materials, such as the Lüshan batholiths (2451 ± 12 Ma) and Shishan monzogranite (2455 ± 32 Ma) [3,66]. Based on these features, the Jurassic granitoid suit was mainly produced by the remelting of ancient mafic lower crust [24]. The presence of gabbro, lamprophyre, tonalite, and mafic microgranular enclaves (MMEs) might suggest that an enriched mantle endmember was involved.

The significant negative $\epsilon_{\text{Nd}}(t)$ values and various initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Jurassic granitoids are consistent with their derivation from ancient lower crust (Figure 11a). A portion of the samples had high negative $\epsilon_{\text{Nd}}(t)$ values, which were similar to the values of the Ordovician kimberlites and mantle xenoliths and the coeval mantle-derived rocks (e.g., gabbro and lamprophyre). However, most of the samples were similar to the Precambrian basement rocks of the NCC. This scenario reflects that the parental magma may be more complicated, including ancient lower crust and minor juvenile lithospheric mantle components. Most of the samples had an old mean $T_{\text{DM}2}$ age of 2.17 Ga and a mean T_{DM^C} age 2.11 Ga, which required an older endmember. The Archean–Paleoproterozoic basement rocks are an optimal component. However, the crustal endmember was probably recently underplated by the Jurassic magmatism, which may, alternatively, indicate mixing with the ancient, enriched lithospheric mantle. The significant negative zircon Hf isotopic compositions also support the proposed Archean lower-crust-extracted felsic magma sources (Figures 10 and 11c). In addition, the slightly higher zircon $\delta^{18}\text{O}$ of the Jurassic Shuihutong and Baijiadian plutons is also very similar to the values of many other NCC granitoids, which are also believed to have been derived from a lower crustal source [66]. The positive $\epsilon_{\text{Hf}}(t)$ values (Lüshan granite, LB64) may represent the involvement of the Paleo-Pacific oceanic subducted slab or underplating by the depleted mantle [68]. The basaltic melts evolved into felsic magmas with minor ancient crustal contamination and then the felsic magmas formed granites with positive $\epsilon_{\text{Hf}}(t)$ values.

7.2. Relationship between the Sources and the Tectonic Setting

The Triassic granitoids were emplaced after the final amalgamation and suturing of the CAOBD with the NCC [62,69]. In the Early Triassic, the high-K calc-alkaline granites (HKCA), including the monzogranite, K-feldspar granite and minor monzonite, were the dominant type of batholith in the Chifeng–Chaoyang district, which is one of the important characteristics of post-collisional magmatic activities [70–72]. In the final stages of orogeny, the HKCA often shift to shoshonitic or alkaline–peralkaline compositions (nepheline syenite, aegirine-augite syenite, pyroxene syenite, quartz syenite, syenite, and alkaline granite) [73,74], which is consistent with the regional lithological associations of the Middle–Late Triassic rocks (Figure 4a). The Triassic Fanshan alkaline ultramafic–syenite complex [75], Late Triassic Guangtoushan alkaline–peralkaline granites [28], and other alkaline rocks [76] support the hypothesis that the magmatic rocks were derived from the melting of an enriched mantle and post-collisional lithospheric extension along the northern margin of the NCC (Figure 12a). Late Triassic to Early Jurassic extensional deformation and large-scale gravity sliding have been identified in western Liaoning Province [76], which represent crustal uplift and rapid exhumation of the crustal rocks.

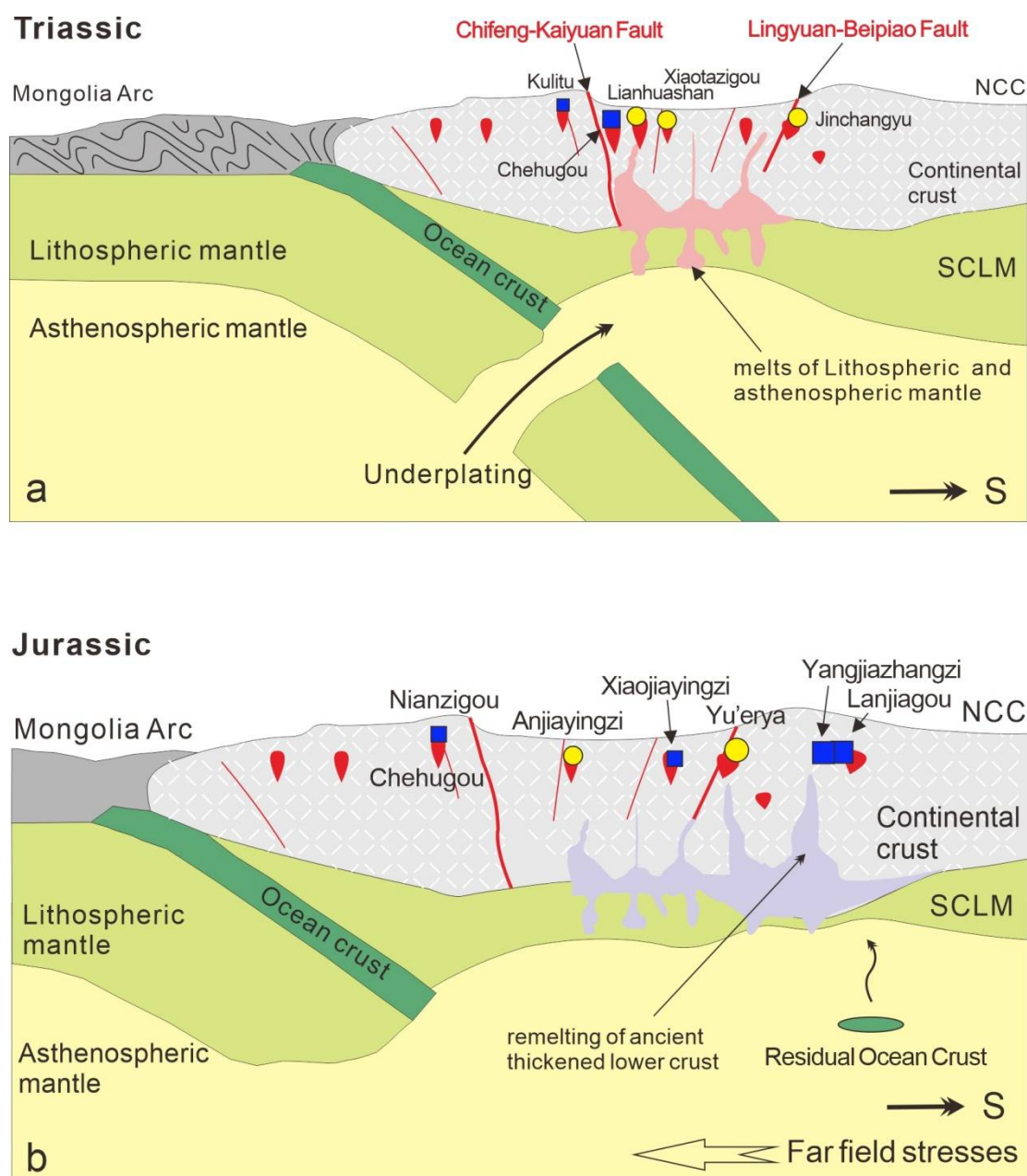


Figure 12. Outline maps of Triassic and Jurassic magmatic source and mineralization. (a) the metallogenic pattern and tectonic setting of study area in Triassic; (b) the metallogenic pattern and tectonic setting of study area in Jurassic.

The Jurassic lithological associations consist of adakitic granite (high-Sr granite), strongly peraluminous leucogranite, high-K calc-alkaline granite, and minor A-type granite (e.g., the Nianzigou pluton). The 42 ages of adakitic granite suggest that it was mainly formed during the late Indosinian to late Yanshanian (229–114 Ma), and ca. 65% of the granites were emplaced in the Jurassic. Adakitic granites are characterized by Sr enrichment, strong HREE depletion, and slightly negative δEu values. These characteristics indicate an adakitic magmatic source generated via the partial melting of crustal rocks under high-temperature (>850 – 900 °C) and high-pressure (≥ 1.5 GPa) conditions, and the original melts lacked fractional crystallization of feldspar [44]. Furthermore, high pressures indicate that the magma was produced deeper than 50 km, which represents an extreme thickened crust [77]. The existence of strongly peraluminous leucogranites (the Madi and

Lüshan plutons) is also robust evidence for a thickened crust in the Chifeng–Chaoyang district. Argillites and sandstones were brought into the deep crust and heated by ocean plate subduction and crustal thickening. The rapid crustal gravity equalization uplift caused partial melting of these heated sedimentary rocks enriched in water-bearing minerals (e.g., muscovite and biotite), producing strongly peraluminous leucogranite. These middle Mesozoic leucogranites (>160 Ma) indicate extreme crustal thickening/uplift. This thickened low crust was reactivated by the northwestward subduction of the Paleo-Pacific oceanic plate (Figure 12b).

The Triassic granitic source contained more juvenile, mantle-derived components. In contrast, the Jurassic granites were derived from the reworking of thickened ancient lower crust. It has been proposed that the most marked change during the Cretaceous cratonic destruction was the change of magmatic source from enriched lithospheric mantle to depleted asthenospheric mantle [2,3]. However, the source transition in the Triassic and Jurassic was from lithospheric mantle and depleted mantle to enriched ancient lower crust in the Chifeng–Chaoyang district. This might indicate that the Jurassic was the key period of tectonic transition from the CAOB to the Paleo-Pacific Ocean regime, and magma sources may be useful indicators to determine the tectonic settings when discrimination diagrams are invalid (Figure 13).

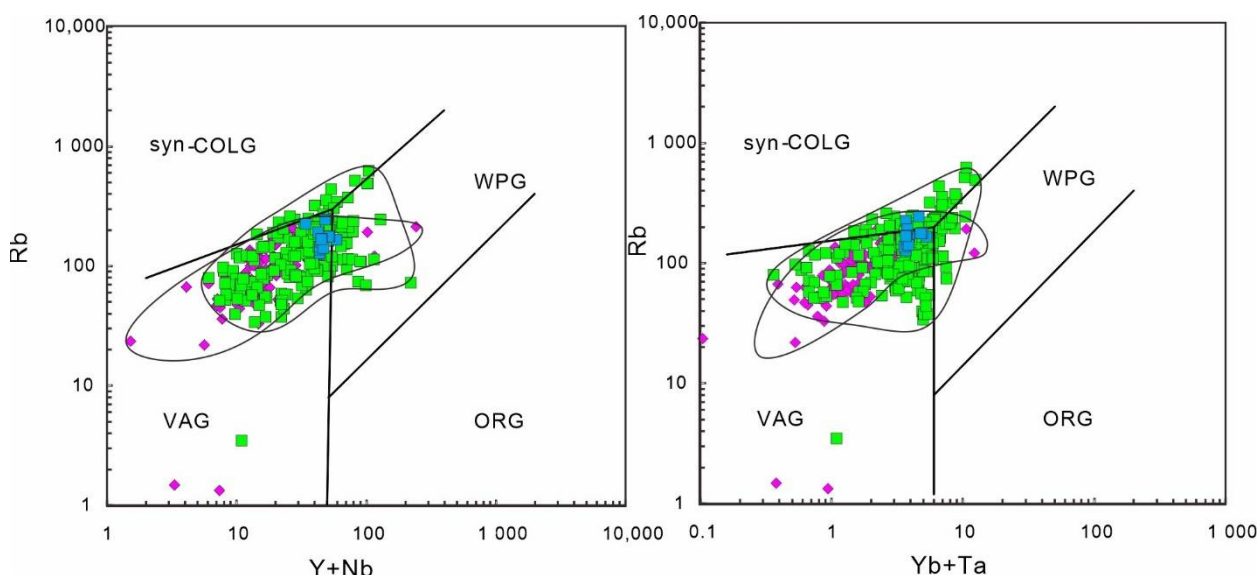


Figure 13. Discrimination diagrams of tectonic setting of granitoids from the Chifeng–Chaoyang district (based on [78]). ORG—ocean-ridge granites; syn-COLG—syn-collisional granites; VAG—volcanic arc granites; WPG—within-plate granites. Data sources and legends are the same as Figure 4.

7.3. Possible Relationship between Sources and Metallogeny

Magmatic intrusions are important lithospheric probes as they come from the deep Earth [79–81]. As powerful tools, the whole-rock Nd and zircon Hf isotopes of magmatic rocks have been broadly used to investigate crustal growth [9], lithospheric architecture, and regional metallogeny. The possible sources and ages of crustal rocks are indicated by ϵ_{Nd} and T_{DM} , respectively. Zircon ϵ_{Hf} data can be used to distinguish between juvenile mantle sources (high positive ϵ_{Hf} values) and ancient crustal sources (negative ϵ_{Hf} values) [82]. Various characteristic values can also be used to estimate the ages and components of mixed magmatic rocks, i.e., between the juvenile mantle and ancient crust endmembers. Furthermore, regional-scale Hf–Nd isotopic mapping can not only precisely identify the deep components and the temporal-spatial distributions, but also explore regional metallogenesis, which provides a new method for investigating the relationship between sources and metallogenesis [48,83].

Several studies linked isotopic architecture to the localization of mineral systems. Mole et al. (2013, 2014) consolidated and extended the Sm–Nd isotope coverage of the Yilgarn Craton and developed a comprehensive understanding of the crustal evolution of the craton and the spatial and temporal occurrence of komatiite-hosted nickel and orogenic gold [84,85]. They showed that the evolving crustal architecture of the Archean Yilgarn Craton played a key role in controlling the location of camp-scale gold, iron, and nickel mineralized systems. Komatiite-hosted nickel deposits cluster into camps localized within young, juvenile crust at the isotopic margin with older lithosphere; orogenic gold systems are typically localized along major structures within juvenile crust; and banded iron formation (BIF)-hosted iron deposits are localized at the edge of, and within, older lithospheric blocks. Based on whole-rock geochemistry and Sr–Nd–Hf isotopic data, Hou et al. (2012) proposed that Cu-bearing magmas were most probably derived from the thickened juvenile mafic lower crust beneath south Tibet. The melting of sulfide-bearing phases in the juvenile mantle components of the Tibetan lower crust probably provided portions of Cu, Au, and S for the fertile magmas. However, the Mo-bearing magmas were likely derived from the partial melting of the ancient Tibetan lower crust, while Mo was also mainly derived from the ancient crust [86]. In China, Nd–Hf isotopic mapping has been conducted in several regions, including the Da Hinggan Mountains [4], the southeastern part of the North China Craton [5], the East Qinling Orogen [6], the Sanjiang Tethyan Orogen [87], the Chinese Altai Orogen [88], and the Himalayan–Tibetan Orogen [89]. Although there is inconsistency regarding some of the specific mineral varieties, the consensus is that the distribution of the copper, gold, and copper-nickel deposits is consistent with the distribution of the juvenile, mantle-derived crust in orogenic belts and cratons, and the large-scale molybdenum deposits occurred in the reworking zone of the Paleoproterozoic ancient crust [48].

In this case, the petrological, geochemical, and Sr–Nd–O–Hf isotopic data provide important constraints on the transition of the magmatic sources from the Triassic to the Jurassic in the Chifeng–Chaoyang district. The Sr–Nd–O–Hf isotopic data indicate that the Triassic magmatism was predominantly produced by the mixing of juvenile lower crust melts derived from the lithospheric mantle and the depleted mantle, which controlled the Au(–Cu) mineralization. However, the Jurassic magmatism, with low $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ values, variable initial $^{87}\text{Sr}/^{86}\text{Sr}$ values, and high model age $T_{\text{DM}2}$ – $T_{\text{DM}C}$ values, was predominantly derived from Archean to Paleoproterozoic reworked crust and controlled the formation of the porphyry-skarn Mo mineralization.

The pattern diagrams are shown in Figure 12. Many studies on typical gold deposits suggested that asthenosphere upwelling triggered the release of gold and sulfur from an enriched and fertilized mantle lithosphere. This mechanism determined that the magma sources must be dominated by juvenile, mantle-derived components with a portion of lower crust (Figure 12a). On the contrary, ancient lower crust is responsible for providing metal Mo, which leads to more enriched isotopic signatures. The thickened lower crust and the thinning of the SCLM promoted large-scale reworking of ancient lower crust, which created favorable conditions for the release of Mo and mineralization (Figure 12b). This study may offer a new direction for studying regional metallogenic patterns.

8. Conclusions

Based on the distributions of the Triassic and Jurassic granites, as well as geochronologic, whole-rock Sr–Nd, and zircon O–Hf isotopic analyses, the primary magmatic sources changed from relatively juvenile, lithospheric, mantle-derived materials to thickened ancient lower crust. They also indicate that the tectonic setting changed from post-collisional extension to subduction of the Paleo-Pacific plate.

The medium–large-scale, high-grade Au deposits are closely related to the Triassic granitoids; however, most of the Mo deposits were formed in the Jurassic. The different magmatic sources in the deep crust controlled the particular type of mineralization.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/min12091117/s1>, Table S1: The age of stocks on the northern margin of North China Craton (NCC); Table S2: Major, trace element, and Sr–Nd isotopic data for the Triassic–Jurassic intrusive rocks in the Chifeng–Chaoyang district; Table S3: Zircon O–Hf isotopic data for the Triassic–Jurassic intrusive rocks in the Chifeng–Chaoyang district; Table S4: Summary of geologic characteristics of major Au–Mo ore deposits in the Chifeng–Chaoyang district. Analytical methods.docx. [90–104].

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Contribution to the Field Statement: This contribution focuses on whether the characteristics of magma source affect the mineralization of gold and molybdenum deposits in the northern margin of North China Craton. This study area has been thought of as an important place for producing numerous large/superlarge deposits, e.g., the Yu’erya gold deposit and the Chehugou molybdenum deposit, as well as episodic felsic intrusions. Based on the comparative analysis of the rock assemblage and geochemical characteristics (majority and trace elements, rare earth elements and Sr–Nd–O–Hf isotopes) of the Triassic and Jurassic intrusions, it is concluded that (1) primary magmatic sources changed from juvenile lithospheric mantle to thickened ancient lower crust between the Triassic and Jurassic; (2) the tectonic setting transited from post-collisional extension to subduction of the Paleozoic-Pacific Plate beneath the East Asia Plate; and (3) different magmatic sources from the deep crust control the particular mineralization during cratonic destruction. Medium–large-scale Au deposits with high grade are closely related to Triassic magmatism; however, most Mo deposits are preferred to the Jurassic magmatic rocks. This pattern is helpful for ore exploration in this region.

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