

Article

Petrogenesis of Middle Triassic Adakite-like Intrusions in the Asiha Orogenic Gold Deposit, East Kunlun Orogenic Belt, China

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Abstract: The East Kunlun Orogenic Belt is considered as one of the important gold mineralization regions in the Tethys tectonic domain. These orogenic gold deposits are related to intermediate-acid intrusions formed at the end of Paleo-Tethys evolution, but the petrogenesis is controversial. This paper presents a new study on the geochemistry of zircon U-Pb, O, S, and Pb isotopic compositions of Asiha quartz diorite, granite porphyry, and sulfides. The geochemical features of quartz diorite and granite porphyry are consistent with the modern adakite, with high content of Sr but low content of Y, Yb, and MgO. Magmatic zircons from these two types of intrusion yielded U-Pb ages of 238.4 ± 1.4 Ma and 240 ± 1.7 Ma, respectively. The high O isotopic composition of Asiha complex may reflect that crust or crustal derivatives were incorporated into the magmatic melt, and the Pb isotope characteristics indicates a lower crust origin. The $\delta^{34}\text{S}$ values of pyrites range from 4.9‰ to 11.6‰. This study infers that the Asiha complex perhaps formed by partial melting of the Paleo-Tethys subducted oceanic crust with seafloor sediments and is markedly different from the traditional adakite. Asiha deposit is an orogenic gold deposit related to adakite-like rocks, which formed in Triassic in the East Kunlun Orogenic Belt.

Keywords: Qinghai-Tibet Plateau; East Kunlun Orogenic Belt; orogenic gold deposits; adakite-like; Middle Triassic; Paleo-Tethys Ocean



Citation: Norbu, N.; Tang, L.; Li, J.; Kong, H.; Li, Y.; Jia, Q.; Xu, Y.

Petrogenesis of Middle Triassic Adakite-like Intrusions in the Asiha Orogenic Gold Deposit, East Kunlun Orogenic Belt, China. *Minerals* **2023**, *13*, 74. <https://doi.org/10.3390/min13010074>

Academic Editor: Michel Faure

Received: 28 November 2022

Revised: 13 December 2022

Accepted: 31 December 2022

Published: 2 January 2023



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1. Introduction

Adakite rock is a result of partial melting of subducted mafic oceanic crust [1]. Other igneous rocks formed in the continental crust subduction stage as well as in the intracontinental stage of evolution with adakitic geochemical features are considered “adakite-like” rocks. The geochemical features of adakites include $\text{Al}_2\text{O}_3 \geq 15$ wt%, $\text{SiO}_2 > 56$ wt%, lower Y and HREE contents, and high Sr [2–5]. Intermediate-acid intrusions with geochemical characteristics of adakite have become one of the important indexes to distinguish Au-Cu mineralization potential [6–9].

The East Kunlun Orogenic Belt (EKOB) is located in the northeast of the Qinghai-Tibet Plateau (Figure 1), and is an important gold mineralization region in the Tethys tectonic domain [10–12]. More than 40 orogenic gold deposits (such as Dachang, Wulonggou, and Guoluolongwa) have been discovered, with proven reserves of gold of 300 t, and the associated metal is Cu. The ore-forming age of these gold deposits is 240–220 Ma and 410–390 Ma, which is a response to the magmatic activity process of the converging plate margin of the Proto-Tethys Ocean and the Paleo-Tethys Ocean [10,12,13]. Previous studies have shown that adakite was formed by subduction or collision in the EKOB at the end of Paleo-Tethys Ocean evolution stage [14,15]. These adakites, including Xintuo monzonitic granite [16], Gouli granodiorite [17], and Asiha granite porphyry and quartz diorite are related to gold deposits in spatial distribution. However, the relationship between these gold deposits and adakites needs to be further clarified.

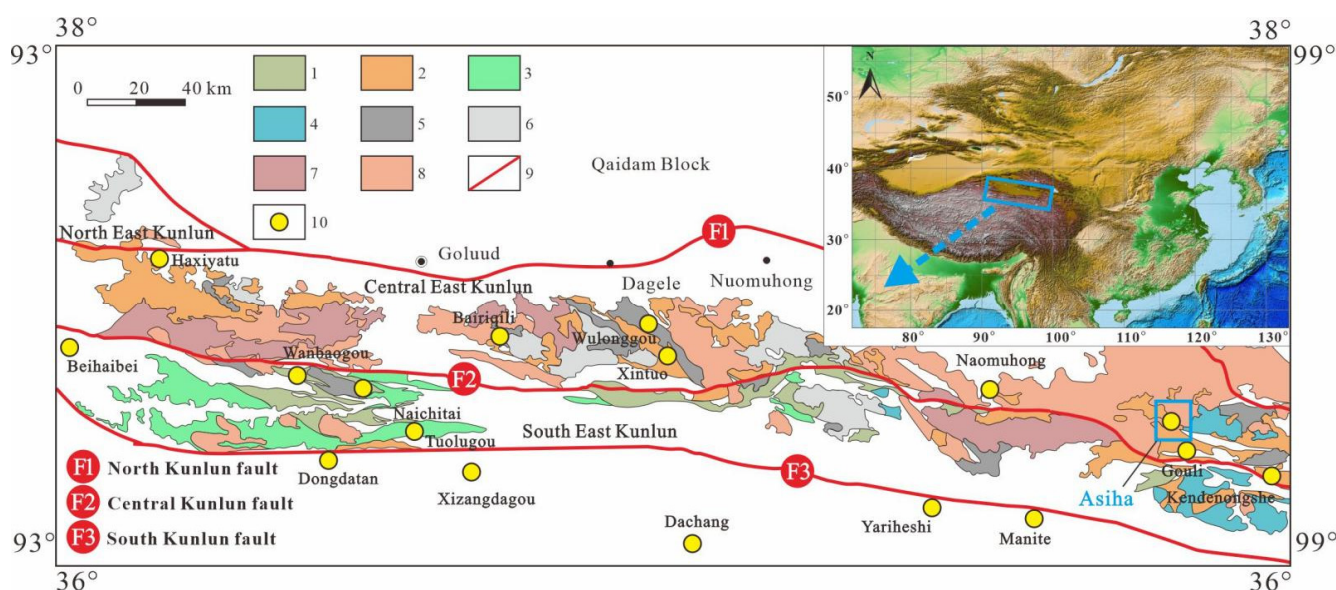


Figure 1. Simplified tectonic units of the East Kunlun Orogenic Belt. 1. Proterozoic Wanbaogou Group; 2. Proterozoic Jinshuikou Group; 3. Proterozoic Nachitai Group; 4. Ordovician intermediate-acid intrusion; 5. Devonian intermediate-acid intrusion; 6. Silurian intermediate-acid intrusion; 7. Permian intermediate-acid intrusion; 8. Triassic intermediate-acid intrusion; 9. Fault; 10. Gold deposit.

In this paper, we selected the Asiha deposit, located in the eastern section of EKOB for research. Field geological survey and mineral element study show that mineralization is related to quartz diorite and granite porphyry. Pyrite in granite porphyry has the same S isotope composition as that in ores, indicating a part of the ore-forming materials in the ore-bodies is from hydrothermal fluid derived from granite porphyry [18]. The formation age of ore-bearing quartz diorite and mafic microgranular enclave (MME) inclusions is 229–228 Ma, with Sr-Nd-Hf isotopic characteristics of mixing of lower crust and enriched mantle-derived magmas [19]. Thus, geological samples (ore-bearing) of granite porphyry and quartz diorite were collected from the Asiha gold deposit. Zircon U-Pb ages and geochemistry of magma intrusions were studied, and O, S, and Pb isotopes were measured. Exploring the deep source process of ore-forming materials provides a new route for the study of regional orogenic gold deposits.

2. Geology Background

2.1. Regional Geology

The EKOB is located in the east of the Tethys tectonic domain [20–22] and has experienced the Proto-Tethys, Paleo-Tethys, and Neo-Tethys evolutionary processes, from the Paleoproterozoic to the present [23–25]. EKOB entered the evolution of the Proto-Tethys stage from Precambrian to Devonian, and the ocean basin subducted in two directions, north and south; finally, the main structural framework of EKOB was formed [25–27]. The Paleo-Tethys evolution began in the Devonian and ended in the Triassic. Voluminous igneous rocks formed in the Permian to Triassic are related to the Paleo-Tethys Ocean subduction and collision. Rock types include diorite, granodiorite, granite, etc. [28,29]. The evolution of the Neo-Tethys had little influence on the EKOB, and only a few magmatic rocks developed during this period. The unconformity control of the Maoniushan Formation and bimodal volcanic rocks indicates that the EKOB entered the Paleo-Tethys rifting process in the Early Devonian [30,31]. Three deep faults (North Kunlun fault, Central Kunlun fault, and South Kunlun fault) divide the EKOB from north to south into Southern, Central, and Northern Kunlun (Figure 1). The exposed rocks include the Proterozoic Wanbaogou Group, Proterozoic Jinshuikou Group, Proterozoic Nachitai Group, and Upper Triassic Elashan Formation [32].

2.2. Geology of the Asiha Gold Deposit

The Asiha gold ore deposit exists in the Asiha complex, which consists of quartz diorite with abundant MMEs, monzogranite, plagiogranite, and diorite. Gold ore-bodies occur mainly within the quartz diorite and granite porphyry (Figure 2a). The Asiha complex intruded into the Proterozoic rocks, which is composed mainly of biotite plagioclase gneiss, which is distributed in the south and northwest area of the ore district. The No. 1 and No. 2 ore-bodies are controlled by the NNE-trending and the NNW-NW-trending faults, respectively, which may be secondary faults of the regional fault (Central Kunlun fault). Structural breccia and fault gouge are developed in the two faults (Figure 2b), which control the distribution of gold ore-bodies [19].

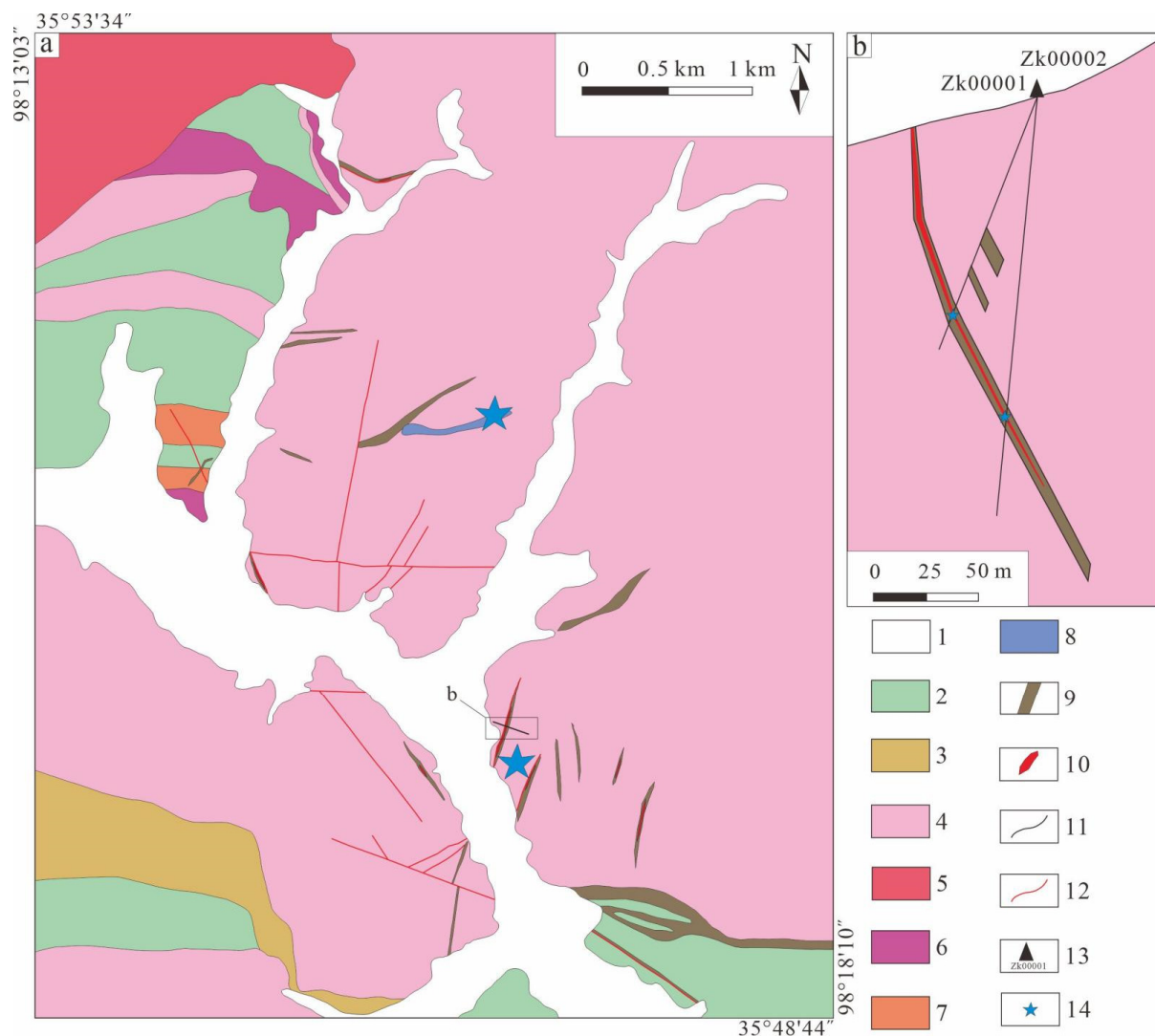


Figure 2. Geological map of Asiha gold deposit (a), Cross section of Line 0 in Figure 2a (b) (modified from [19]). 1. Quaternary; 2. Proterozoic migmatite; 3. Proterozoic gneiss; 4. Quartz diorite; 5. Monzogranite; 6. Plagiogranite; 7. Diorite; 8. Granite porphyry; 9. Fractured alteration zone; 10. Gold orebodies; 11. Geological boundary; 12. Fault; 13. Drillcore; 14. Sample location.

Thirty-three gold ore-bodies and 1 copper ore-body have been identified in the Asiha deposit. The gold ore-bodies are 227–555 m in length and 0.89–1.58 m in thickness, with an average grade of 9.1 g/t. The ore types are mainly structural altered rock type and quartz vein type. Based on field geology and mineral assembles, the mineralization at Asiha can be divided into two mineralization periods: the hydrothermal period and the supergene oxidation period.

The hydrothermal period can be subdivided into three stages: (1) The quartz-pyrite-arsenopyrite stage; pyrite is euhedral-hemihedral, arsenopyrite is coarse-grained euhedral, gold and arsenopyrite are associated. (2) The quartz-polymetallic sulfide stage; chalcopyrite is vein-like, and bismuth is metasomatic chalcopyrite, and all are metasomatic earlier arsenopyrite or pyrite. Pyrite mineralization occurs, and the arsenopyrite, pyrite and quartz veins formed in the early stage are fractured under tectonic stress. This stage is the main stage of gold formation. (3) The quartz-carbonate veins appeared in this stage, and gold mineralization ended. The quartz-polymetallic sulfide stage is the primary stage for gold mineralization [33]. Metallic minerals in the ore rocks are pyrite, chalcopyrite, arsenopyrite, galena, marcasite, pyrrhotite, and native gold. The ore structures include massive, vein, stockwork, vesicular, and disseminated structures. The ore textures include cataclastic, metasomatic, and anhedral granular texture. Wall rock alteration consists mainly of silicification, sericitization, pyritization, chloritization, carbonatation, kaolinization, potassic alteration, ferritization, jarosite, and malachite. Among them, silicification, sericitization, pyritization, and chloritization are closely related to gold mineralization [19]. Other alterations are mostly distributed symmetrically along both sides of the quartz veins.

3. Sampling and Analytical Methodology

3.1. Sample Descriptions

The quartz diorite and granite porphyry samples in this study were collected near the 3680 m footwall in the No. 2 ore-body and in the field outcrop (Figure 2b), respectively. Sulfide samples were collected from drill core. Other granitoids samples were collected from the outcrop of the Asiha complex. The sample is fresh without alteration.

The quartz diorite is located in the eastern section of the study area. It comprises plagioclase 60%, K-feldspar 15%, quartz 15%, amphibole 5%, biotite 5%, and minor zircon and apatite (Figure 3a). Plagioclase is subhedral and shows a distinct polysynthetic twinning texture. Quartz occurs as anhedral crystals, which are intergrowths with plagioclases. Dark minerals are mainly biotite and amphibole, which occur as schistose and columnar, respectively.

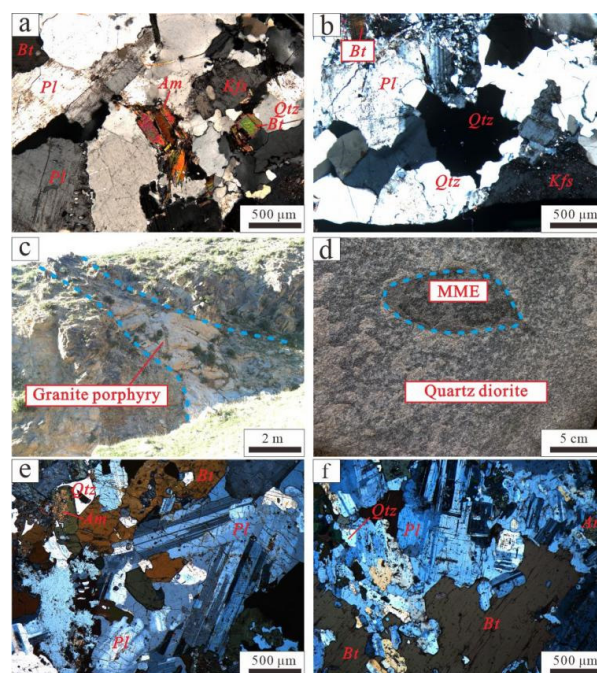


Figure 3. Photographs and photomicrographs of typical lithofacies from the Asiha complex. Photomicrographs of Quartz diorite (a). Photomicrographs of granite porphyry (b). The typical photographs of the granite porphyry (c), quartz diorite and MMEs in the field (d). Photomicrographs of MMEs (e,f). Pl = plagioclase, Kfs = K-feldspar, Qtz = quartz, Am = amphibole, and Bt = biotite.

Granite porphyry has a porphyritic texture and is composed of 40% plagioclase, 35% K-feldspar, 20% quartz, 5% biotite, and minor zircon and sphene (Figure 3b,c). K-feldspar has Carlsbad twin, and plagioclase has polysynthetic twin. Potassic feldspar has alterations such as kaolinization and argillization.

MMEs are widely distributed within the quartz diorite (Figure 3d), with a diameter from several to fifty centimeters, and generally display ellipsoidal, or less commonly, lenticular or irregular shape. MMEs are dark grey and have a fine-to-medium-grained texture, and the rock type is diorite. They consist mainly of 50% plagioclase, 25% biotite, 20% amphibole, and 5% quartz (Figure 3e,f).

3.2. Analytical Methodology

Zircon U-Pb determinations were carried out by LA-ICP-MS at the State Key Laboratory of Continental Dynamics of Northwest University, Xi'an, China. Zircon isotopic determinations were obtained with a spot size of 32 μm . The detailed parameters and operating methods of the instrument have been published previously [34].

Major and trace elements were analyzed at the Western Mineral Resources and Geological Engineering Key Laboratory of the Ministry of Education. The major elements were identified by using X-ray fluorescence spectroscopy (XRF), following the procedure of [35]. The analytical error is less than 1%. Trace elements were identified using a PQ2 Turbo ICP-MS following the technique of [36]. The precision was generally <5‰ for trace elements.

Isotope analysis was performed at the Test Center of Beijing Research Institute of Uranium Geology. Twelve samples, including granite porphyry, quartz diorite, and granodiorite, were obtained from the Asihua complex and used for whole-rock O isotope analysis. Oxygen isotopic composition was measured on a MAT 253. Sulfide was obtained from ores for S and Pb isotopic analysis. A Finnigan MAT 251 mass spectrometer was utilized to analyze the S isotopic composition. Plumbum isotopic composition was measured on an ISOPROBE-T Thermal Ionization Mass Spectrometer with the standard NBS SRM 981. The detailed parameters and operating methods of O, S, and Pb isotopes have been published previously [37].

4. Analytical Results

4.1. Zircon U-Pb Ages

The U-Pb dating data of 40 individual zircon crystals from quartz diorite and 29 individual zircon crystals from granite porphyry are listed in Table 1. Zircons have clear oscillatory zonation in cathodoluminescence images (Figure 4). The zircon Th/U ratio of quartz diorite range from 0.53 to 1.15, with an average of 0.75. The zircon Th/U ratio of granite porphyry varies from 0.48 to 0.94, with a mean value 0.69. The quartz diorite and the granite porphyry yielded a weighted age of 238.4 ± 1.4 Ma (Figure 4a) and 240 ± 1.7 Ma (Figure 4b), respectively.

Table 1. LA-ICP-MS zircon U-Pb dating results of Asiha complex.

Sample	Sample No.	(ppm)			Th/U	Isotope Ratio						Age (Ma)					
		Pb	Th	U		²⁰⁷ Pb/ ²⁰⁶ Pb	1 σ	²⁰⁷ Pb/ ²³⁵ U	1 σ	²⁰⁶ Pb/ ²³⁸ U	1 σ	²⁰⁷ Pb/ ²⁰⁶ Pb	1 σ	²⁰⁷ Pb/ ²³⁵ U	1 σ	²⁰⁶ Pb/ ²³⁸ U	1 σ
Granite porphyry	1	5.4	74.8	114.1	0.66	0.0491	0.0028	0.2556	0.0126	0.0378	0.0007	152	126	231	10	239	4
	2	4.8	74.3	95.0	0.78	0.0535	0.0029	0.2780	0.0133	0.0377	0.0007	351	119	249	11	238	4
	3	4.9	67.4	94.3	0.72	0.0494	0.0027	0.2597	0.0123	0.0381	0.0007	166	122	234	10	241	4
	4	4.1	52.8	83.4	0.63	0.0489	0.0029	0.2561	0.0136	0.0380	0.0007	141	134	232	11	241	5
	5	4.5	69.9	89.8	0.78	0.0547	0.0030	0.2837	0.0138	0.0376	0.0007	400	119	254	11	238	4
	6	6.9	73.3	138.3	0.53	0.0529	0.0028	0.2794	0.0125	0.0384	0.0007	322	114	250	10	243	4
	7	8.0	100.7	170.5	0.59	0.0525	0.0024	0.2701	0.0100	0.0373	0.0007	307	99	243	8	236	4
	8	5.9	80.7	124.2	0.65	0.0510	0.0026	0.2626	0.0113	0.0373	0.0007	241	111	237	9	236	4
	9	6.5	71.2	132.6	0.54	0.0492	0.0023	0.2608	0.0103	0.0384	0.0007	159	107	235	8	243	4
	10	5.0	71.4	100.1	0.71	0.0483	0.0028	0.2513	0.0132	0.0377	0.0007	115	133	228	11	239	5
	11	6.0	88.5	112.5	0.79	0.0515	0.0025	0.2745	0.0113	0.0387	0.0007	263	107	246	9	245	4
	12	6.0	90.2	114.6	0.79	0.0516	0.0027	0.2720	0.0121	0.0382	0.0007	270	114	244	10	242	4
	13	4.8	63.5	99.0	0.64	0.0549	0.0031	0.2887	0.0142	0.0381	0.0008	408	120	258	11	241	5
	14	5.6	73.8	107.9	0.68	0.0497	0.0025	0.2608	0.0112	0.0381	0.0007	180	112	235	9	241	4
	15	5.3	85.5	101.6	0.84	0.0506	0.0027	0.2664	0.0126	0.0382	0.0007	221	120	240	10	242	4
	16	5.5	85.7	104.8	0.82	0.0528	0.0026	0.2796	0.0120	0.0384	0.0007	320	109	250	9	243	4
	17	7.1	128.6	132.6	0.97	0.0546	0.0030	0.2821	0.0135	0.0374	0.0007	398	117	252	11	237	5
	18	5.0	74.5	99.6	0.75	0.0492	0.0029	0.2581	0.0135	0.0380	0.0008	159	131	233	11	241	5
	19	5.1	86.1	105.3	0.82	0.0526	0.0049	0.2768	0.0243	0.0381	0.0010	313	199	248	19	241	6
	20	4.3	59.6	85.1	0.70	0.0524	0.0030	0.2742	0.0140	0.0380	0.0008	301	126	246	11	240	5
	21	5.0	70.9	100.7	0.70	0.0550	0.0032	0.2886	0.0152	0.0381	0.0008	411	126	258	12	241	5
	22	5.6	98.2	109.9	0.89	0.0511	0.0031	0.2638	0.0144	0.0375	0.0008	243	134	238	12	237	5
	23	7.6	116.6	158.2	0.74	0.0549	0.0029	0.2814	0.0129	0.0372	0.0007	408	114	252	10	235	4
	24	3.8	50.9	75.1	0.68	0.0517	0.0032	0.2723	0.0150	0.0382	0.0008	274	134	245	12	241	5
	25	6.2	92.2	123.0	0.75	0.0486	0.0025	0.2542	0.0115	0.0379	0.0007	129	118	230	9	240	4
	26	7.2	164.2	143.3	1.15	0.0509	0.0034	0.2669	0.0164	0.0380	0.0008	236	148	240	13	241	5
	27	7.4	132.6	135.8	0.98	0.0520	0.0025	0.2720	0.0109	0.0380	0.0007	284	105	244	9	240	4

Table 1. Cont.

Sample	Sample No.	(ppm)			Th/U	Isotope Ratio						Age (Ma)					
		Pb	Th	U		²⁰⁷ Pb/ ²⁰⁶ Pb	1 σ	²⁰⁷ Pb/ ²³⁵ U	1 σ	²⁰⁶ Pb/ ²³⁸ U	1 σ	²⁰⁷ Pb/ ²⁰⁶ Pb	1 σ	²⁰⁷ Pb/ ²³⁵ U	1 σ	²⁰⁶ Pb/ ²³⁸ U	1 σ
Quartz diorite	28	6.0	83.9	124.2	0.68	0.0486	0.0028	0.2541	0.0132	0.0380	0.0008	126	131	230	11	240	5
	29	4.8	72.9	97.6	0.75	0.0486	0.0031	0.2526	0.0148	0.0377	0.0008	130	145	229	12	238	5
	1	27.6	100.6	153.6	0.65	0.0513	0.0022	0.2671	0.0091	0.0377	0.0007	255	95	240	7	239	4
	2	20.4	73.1	112.1	0.65	0.0511	0.0024	0.2660	0.0105	0.0377	0.0007	246	106	240	8	239	4
	3	35.9	120.0	209.7	0.57	0.0501	0.0020	0.2588	0.0078	0.0375	0.0007	201	90	235	6	239	4
	4	17.3	67.0	95.7	0.7	0.0569	0.0027	0.2934	0.0116	0.0374	0.0007	468	104	260	9	238	4
	5	22.6	95.5	127.1	0.75	0.0528	0.0024	0.2743	0.0099	0.0377	0.0007	318	98	246	8	239	4
	6	18.3	71.4	109.0	0.66	0.0509	0.0024	0.2639	0.0104	0.0376	0.0007	213	108	237	9	239	4
	7	22.2	86.2	128.1	0.67	0.0520	0.0024	0.2684	0.0099	0.0374	0.0007	289	103	244	8	239	4
	8	13.8	45.8	78.7	0.58	0.0522	0.0029	0.2694	0.0131	0.0374	0.0007	308	126	245	11	239	5
	9	18.6	53.2	109.0	0.49	0.0531	0.0024	0.2746	0.0104	0.0375	0.0007	335	101	246	8	237	4
	10	12.8	37.7	76.1	0.5	0.0530	0.0031	0.2736	0.0141	0.0374	0.0007	289	132	244	12	239	5
	11	28.3	133.6	162.5	0.82	0.0525	0.0022	0.2708	0.0089	0.0374	0.0007	280	95	243	7	239	4
	12	24.5	96.0	147.9	0.65	0.0526	0.0023	0.2692	0.0092	0.0371	0.0007	323	99	245	8	237	4
	13	34.1	182.1	194.7	0.94	0.0596	0.0023	0.3084	0.0090	0.0375	0.0007	482	89	266	8	242	4
	14	23.7	82.1	134.1	0.61	0.0510	0.0023	0.2644	0.0094	0.0376	0.0007	242	98	238	8	238	4
	15	18.1	53.7	112.5	0.48	0.0512	0.0027	0.2651	0.0118	0.0376	0.0007	250	116	239	10	238	4
	16	17.2	51.4	101.3	0.51	0.0702	0.0031	0.3657	0.0127	0.0378	0.0007	259	99	240	8	239	4
	17	39.3	83.1	101.5	0.82	0.0864	0.0037	0.4496	0.0149	0.0377	0.0007	264	87	242	6	240	4
	18	24.8	116.2	146.8	0.79	0.0520	0.0022	0.2670	0.0091	0.0372	0.0007	363	90	250	7	238	4
	19	37.8	182.8	218.3	0.84	0.0515	0.0020	0.2693	0.0079	0.0379	0.0007	236	101	237	8	237	4
	20	31.1	110.1	180.8	0.61	0.0538	0.0022	0.2790	0.0089	0.0376	0.0007	199	121	235	10	238	5
	21	22.3	86.7	136.1	0.64	0.0505	0.0023	0.2589	0.0099	0.0372	0.0007	213	112	236	9	238	4
	22	22.7	116.1	137.6	0.84	0.0505	0.0026	0.2570	0.0111	0.0369	0.0007	195	93	234	7	238	4
	23	19.6	74.1	120.7	0.61	0.0509	0.0026	0.2620	0.0115	0.0373	0.0007	265	110	240	9	238	4
	24	37.6	190.6	223.6	0.85	0.0503	0.0020	0.2589	0.0080	0.0373	0.0007	161	104	231	8	238	4
	25	21.9	84.8	117.7	0.72	0.0761	0.0032	0.3921	0.0126	0.0374	0.0007	242	113	239	9	239	4

Table 1. Cont.

Sample	Sample No.	(ppm)			Th/U	Isotope Ratio						Age (Ma)					
		Pb	Th	U		²⁰⁷ Pb/ ²⁰⁶ Pb	1 σ	²⁰⁷ Pb/ ²³⁵ U	1 σ	²⁰⁶ Pb/ ²³⁸ U	1 σ	²⁰⁷ Pb/ ²⁰⁶ Pb	1 σ	²⁰⁷ Pb/ ²³⁵ U	1 σ	²⁰⁶ Pb/ ²³⁸ U	1 σ
	26	19.6	89.4	118.6	0.75	0.0517	0.0026	0.2654	0.0111	0.0372	0.0007	317	105	246	9	239	4
	27	23.9	93.8	138.7	0.68	0.0489	0.0023	0.2512	0.0096	0.0373	0.0007	207	113	235	9	238	4
	28	23.0	113.2	134.0	0.85	0.0505	0.0024	0.2588	0.0105	0.0372	0.0007	247	104	239	8	239	4
	29	21.4	83.5	128.9	0.65	0.0533	0.0025	0.2742	0.0103	0.0373	0.0007	184	107	233	8	238	4
	30	20.5	73.2	118.7	0.62	0.0503	0.0025	0.2590	0.0109	0.0374	0.0007	364	102	252	9	240	4
	31	23.7	95.9	138.2	0.69	0.0512	0.0023	0.2632	0.0097	0.0373	0.0007	326	123	245	11	237	5
	32	25.4	127.2	147.9	0.86	0.0495	0.0022	0.2527	0.0094	0.0370	0.0007	197	90	235	6	239	4
	33	21.3	84.0	126.7	0.66	0.0528	0.0024	0.2726	0.0103	0.0375	0.0007	422	124	253	11	236	5
	34	24.8	46.7	76.4	0.61	0.1402	0.0069	0.7326	0.0295	0.0379	0.0008	169	133	233	11	239	5
	35	19.7	70.7	103.5	0.68	0.0691	0.0030	0.3577	0.0125	0.0375	0.0007	255	95	240	7	239	4
	36	22.2	106.3	131.2	0.81	0.0519	0.0027	0.2664	0.0117	0.0372	0.0007	246	106	240	8	239	4
	37	45.2	162.6	268.4	0.61	0.0502	0.0019	0.2558	0.0071	0.0369	0.0006	201	90	235	6	239	4
	38	29.8	153.0	167.7	0.91	0.0588	0.0025	0.3020	0.0100	0.0372	0.0007	468	104	260	9	238	4
	39	18.8	64.9	109.5	0.59	0.0563	0.0033	0.2884	0.0149	0.0371	0.0008	318	98	246	8	239	4
	40	18.2	76.1	105.3	0.72	0.0498	0.0027	0.2543	0.0119	0.0370	0.0007	213	108	237	9	239	4

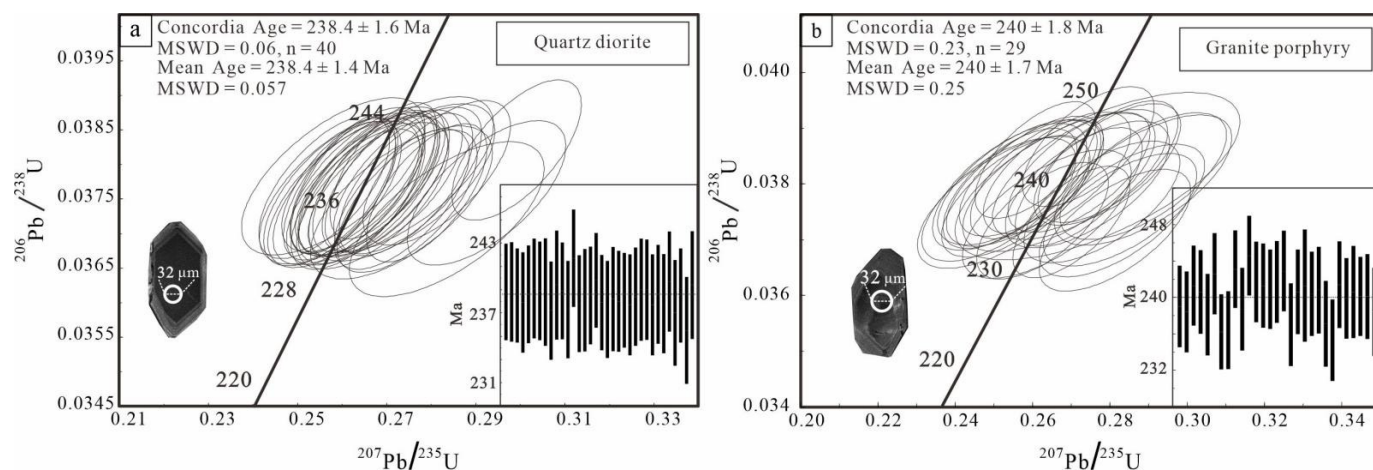


Figure 4. Zircon U-Pb isotope concordia plot for quartz diorite (a) and granite porphyry (b) in Asiha gold deposit.

4.2. Major and Trace Elements

The SiO_2 , CaO , Al_2O_3 , Na_2O , and K_2O content of quartz diorite is 60.45–62.49 wt%, 5.29–5.97 wt%, 16.88–17.2 wt%, 3.4–3.54 wt%, and 2–2.51 wt%, respectively (Table 2). Compared to the quartz diorite samples, the granite porphyry samples show higher SiO_2 (68.24–69.45 wt%) and K_2O (2.52–3.12 wt%) contents and lower Al_2O_3 (15.1–15.44 wt%) and CaO (2.44–3.54 wt%) concentration. All samples are metaluminous (Figure 5a), with A/CNK ratios of 0.92 to 1.04, belonging to the calc-alkaline series (Figure 5b). The total content of REE is between 131 and 171 ppm, with strongly fractionated REE patterns ($\text{LREE/HREE} = 10.32\text{--}13.96$) (Figure 5c). The primitive mantle normalized trace-element diagram shows that Rb, Th, Nd, Sm, and Hf are enriched, while Ba, Nb, and Ti are depleted (Figure 5d). In addition, quartz diorite samples are depleted in Ta and Zr, and granite porphyry samples are depleted in Sr.

Table 2. Major elements (%) and trace elements (ppm) of Asiha complex.

Sample Types	Quartz Diorite					Granite Porphyry		
Sample No.	11ASY003	11ASY005	11ASY006	11ASY008	11ASBY05	12ASB02	12ASB03	12ASB04
SiO_2	60.45	62.44	62.49	61.08	60.90	69.26	69.45	68.24
TiO_2	0.71	0.67	0.61	0.67	0.71	0.32	0.29	0.30
Al_2O_3	17.20	16.88	16.90	17.17	17.04	15.32	15.44	15.10
MnO	0.09	0.09	0.09	0.09	0.09	0.05	0.04	0.05
MgO	3.33	2.74	2.66	3.06	2.78	0.40	0.43	0.39
CaO	5.97	5.29	5.47	5.36	5.32	2.49	2.44	3.54
Na_2O	3.43	3.48	3.53	3.54	3.40	3.89	3.74	3.60
K_2O	2.00	2.25	2.28	2.26	2.51	3.12	3.09	2.52
P_2O_5	0.18	0.17	0.17	0.18	0.17	0.10	0.09	0.09
Fe_2O_3	1.25	1.43	1.23	1.15	1.24	1.31	1.35	1.05
FeO	4.22	3.49	3.47	3.96	4.00	1.26	1.00	1.26
Lol	1.15	1.10	1.13	1.47	1.81	2.38	2.58	3.80
Total	99.98	100.03	100.03	99.99	99.97	99.90	99.94	99.94
La	35.10	26.90	36.70	37.40	34.50	36.20	35.00	35.80
Ce	65.30	58.70	74.00	73.80	70.20	66.50	62.10	63.40

Table 2. Cont.

Sample Types	Quartz Diorite				Granite Porphyry			
Sample No.	11ASY003	11ASY005	11ASY006	11ASY008	11ASBY05	12ASB02	12ASB03	12ASB04
Pr	6.93	6.18	8.42	8.50	8.02	7.22	6.99	7.06
Nd	25.90	22.60	31.80	31.70	30.10	26.70	23.90	24.40
Sm	5.10	4.57	5.59	5.59	5.56	4.30	4.26	4.15
Eu	1.30	1.16	1.30	1.39	1.24	0.93	0.90	0.92
Gd	4.20	3.82	4.78	4.58	4.59	3.25	3.33	3.18
Tb	0.60	0.54	0.66	0.65	0.66	0.49	0.51	0.48
Dy	3.32	3.16	3.81	3.60	3.68	2.64	2.64	2.54
Ho	0.64	0.60	0.70	0.68	0.70	0.52	0.52	0.48
Er	1.67	1.61	1.90	1.87	1.92	1.46	1.44	1.31
Tm	0.25	0.23	0.26	0.26	0.27	0.22	0.22	0.20
Yb	1.53	1.46	1.71	1.66	1.80	1.39	1.45	1.30
Lu	0.23	0.21	0.24	0.24	0.26	0.23	0.24	0.23
Y	17.40	17.00	17.80	18.60	19.60	15.00	15.90	14.60
Rb	95.60	93.60	107.00	102.00	122.00	165.00	162.00	154.00
Ba	710.00	588.00	635.00	669.00	609.00	815.00	784.00	884.00
Th	9.67	7.45	16.80	13.40	11.20	16.30	16.60	16.40
U	1.71	1.22	1.77	2.35	1.12	2.76	2.32	2.33
Ta	0.81	0.64	0.69	0.63	0.71	1.61	1.62	1.59
Nb	10.50	9.84	9.91	9.96	11.50	12.90	13.00	12.70
Sr	558.00	523.00	558.00	563.00	491.00	406.00	456.00	378.00
Zr	30.70	28.80	23.40	23.90	39.20	158.00	138.00	136.00
Hf	3.92	1.87	4.13	3.16	2.54	4.64	4.26	4.06
ΣREE	152.07	131.74	171.87	171.92	163.50	152.05	143.50	145.45
ΣLREE	139.63	120.11	157.81	158.38	149.62	141.85	133.15	135.73
ΣHREE	12.44	11.63	14.06	13.54	13.88	10.20	10.35	9.72
LREE/HREE	11.22	10.33	11.22	11.70	10.78	13.91	12.86	13.96
δEu	0.83	0.83	0.75	0.82	0.73	0.73	0.71	0.75
δCe	0.95	1.06	0.98	0.96	0.98	0.94	0.90	0.91
(La/Sm) _N	4.33	3.70	4.13	4.21	3.90	5.30	5.17	5.43
(La/Yb) _N	15.47	12.42	14.47	15.19	12.92	17.56	16.27	18.57
(Sm/Nd) _N	0.61	0.62	0.54	0.54	0.57	0.50	0.55	0.52
(Gd/Yb) _N	2.22	2.11	2.26	2.23	2.06	1.89	1.85	1.97
A/NK	2.20	2.07	2.04	2.08	2.05	1.46	1.52	1.63
A/CNK	0.92	0.95	0.93	0.95	0.95	1.00	1.04	0.93

Note: LOI = Loss on ignition; A/CNK = $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$; A/NK = $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})$; LREE = light rare-earth element; and HREE = heavy rare-earth element.

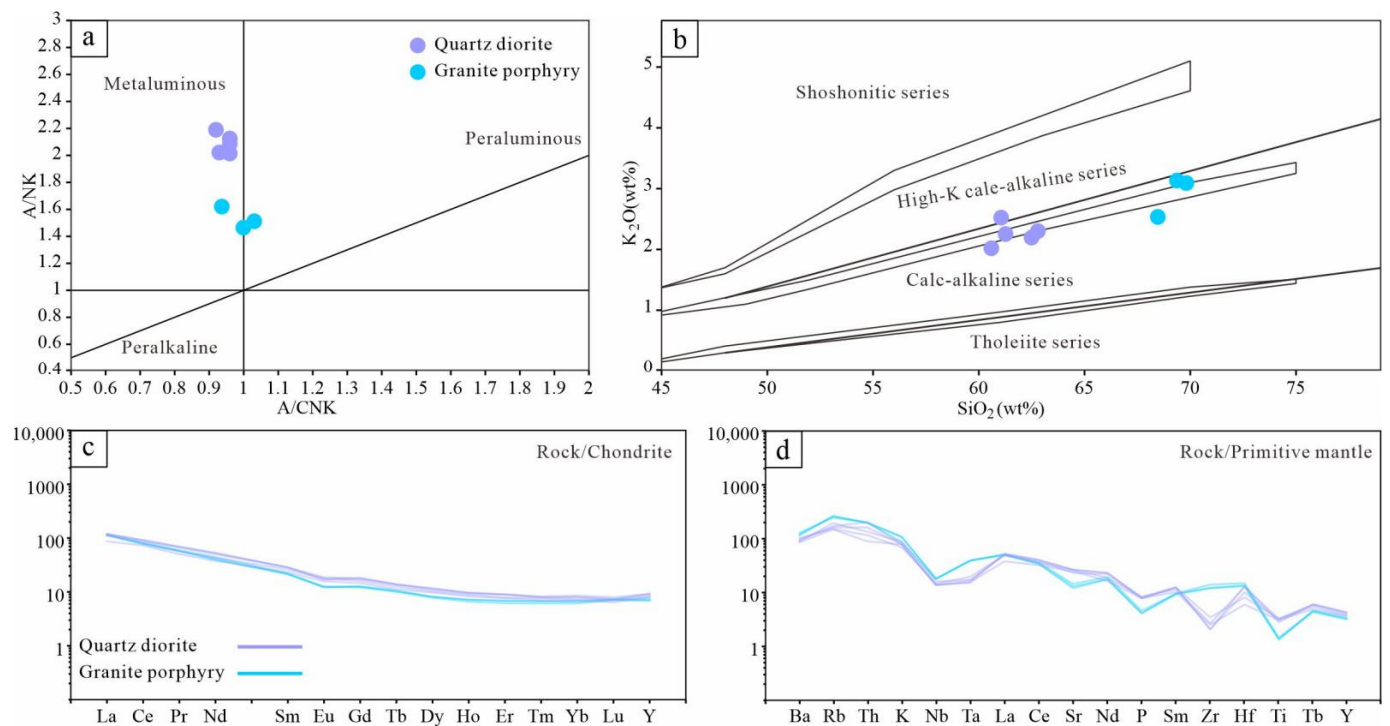


Figure 5. Discrimination diagrams for the granitoid. A/CNK–A/NK (a), SiO₂–K₂O (b) diagrams, chondrite-normalized REE diagram (c), and primitive mantle-normalized trace element spider diagram (d). Figure 5a is modified from [38]. Figure 5b is modified from [39]. Primitive mantle data are from [40,41].

4.3. O–S–Pb Isotopes

Oxygen isotope data for the Asih complex are presented in Table 3. The $\delta^{18}\text{O}_{\text{V-SMOW}}$ values of 12 samples range from 8.9‰ to 15.8‰, and are 12.28‰ on average. The mean $\delta^{18}\text{O}_{\text{V-SMOW}}$ value of quartz diorite and granite porphyry related to mineralization is 13.25‰, which is obviously higher than that of non-ore-bearing granite pluton, with a mean value of 10.35‰.

Table 3. Oxygen isotopic compositions of Asih complex.

Sample Types	$\delta^{18}\text{O}_{\text{V-PDB}} \text{‰}$	$\delta^{18}\text{O}_{\text{V-SMOW}} \text{‰}$
Monzogranit	−21.3	8.9
	−19.8	10.4
Plagiogranite	−19.7	10.6
	−18.8	11.5
Granite porphyry	−19.3	11
	−21.3	8.9
	−16.8	13.6
	−18.3	12
Quartz diorite	−15.7	14.7
	−15.7	14.8
	−15.2	15.2
	−14.6	15.8

Note: PDB = Pee Dee Belemnite, and SMOW = Standard Mean Ocean Water.

The S isotope compositions are shown in Table 4. The $\delta^{34}\text{S}_{\text{V-CDT}}$ values of pyrite samples are from 4.9‰ to 6.3‰, with a medium of 5.4‰. The Pb isotope compositions from this study and referenced data are listed in Table 5. Pyrite samples have relatively homogeneous, low radiogenic Pb isotope compositions. The $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ values of pyrites are 18.072–18.508, 15.561–15.675, and 38.172–38.904, respectively. The $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ values from the Asiha complex are 18.548–19.268, 15.624–15.771, and 38.883–39.983, respectively.

Table 4. Sulfur isotopic compositions of pyrite.

Sample No.	Minerals	$\delta^{34}\text{S}_{\text{V-CDT}}$ (‰)
13ASII-2	Pyrite	11.6
13ASII-3		6.2
13ASII-4		5.0
13ASI-2		6.3
11ASPD002		5.6
11ASY010		4.9
11ASY010		4.9
12ASPD01		5.1
12ASY010		5.2

Note: CDT = Canyon Diablo Meteorite.

Table 5. Lead isotopic compositions of Asiha complex and pyrite.

Sample Types	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{206}\text{Pb}/^{204}\text{Pb}$
Pyrite	38.429	15.635	18.387
	38.555	15.666	18.421
	38.172	15.561	18.072
	38.415	15.613	18.398
	38.429	15.604	18.450
	38.416	15.605	18.416
	38.388	15.599	18.441
	38.904	15.675	18.508
Quartz diorite	39.289	15.668	18.927
	39.034	15.646	19.051
	38.976	15.626	18.872
	39.002	15.624	18.942
	39.531	15.688	19.137
Granite porphyry	39.607	15.771	19.268
	39.555	15.742	19.054
	39.983	15.691	18.819
	39.321	15.763	18.947
	39.815	15.645	18.548
	39.275	15.647	18.846
	38.883	15.676	18.644

5. Discussion

5.1. Petrogenesis and Source of Adakite-like

Previous research summarized that vast majority gold-bearing intrusive rocks in EKOB are generally I-type granites, and the Sr-Nd-Hf isotope composition of these I-type granites are consistent with the MMEs. They are considered to be formed by the mixing of mantle-derived and crust-derived magmas [19,42–44]. Quartz diorite depleted in Ta and granite porphyry depleted in Sr represent that they experienced significant separation and crystallization of rutile and plagioclase, respectively [45]. The quartz diorite and granite porphyry samples have SiO₂ (60.45–69.45 wt%), Sr (378–563 ppm), and Al₂O₃ (15.1–17.2 wt%) contents but low Y (14.6–19.6 ppm), MgO (0.39–3.33 wt%), and Yb (1.3–1.8 ppm) contents. These features are similar to modern adakite [1].

In the Yb_N vs. La_N/Yb_N (Figure 6a) diagrams, the samples are plotted into the adakitic field. In fact, many gold ore-forming bodies previously considered as A-type or I-type granite show the adakitic rock characteristics (e.g., Wulonggou, Xizangdagou, and Heihaibei). However, the magmatic rocks associated with the Triassic porphyry-skarn Fe-Pb-Zn deposit are not adakite. Instead, they are associated with I-type granites (e.g., Reshui and Duolongqiarou) [46]. In the Y vs. Nb diagrams, our samples are located in the volcanic arc and syn-collision field (Figure 6b), and the granite porphyry rocks are located in syn-collision field (Figure 6c), indicating that the formation environment of Asiha complex may be the transition period between subduction environment and collision environment.

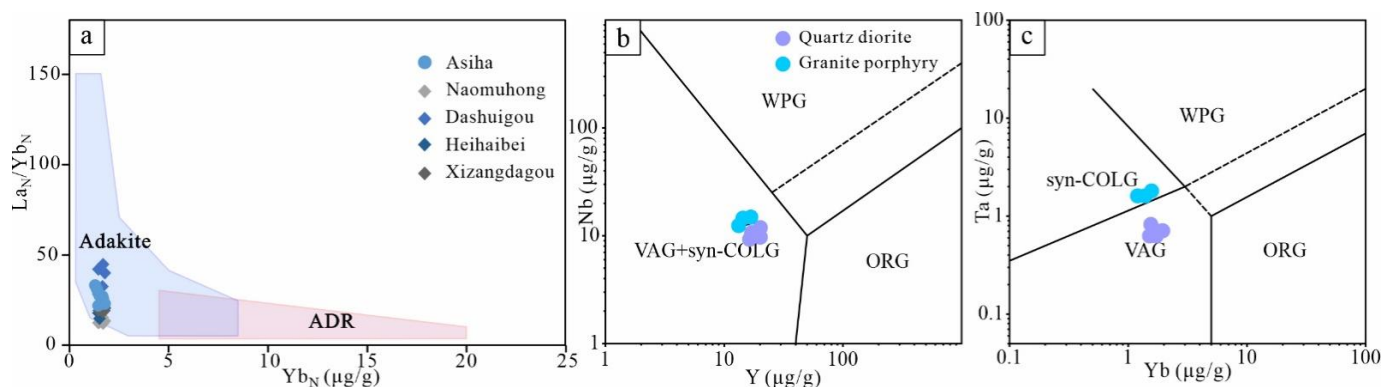


Figure 6. Discrimination diagrams for the granitoids origin, La_N/Yb_N vs. Yb_N (a), Y vs. Nb (b), Yb vs. Ta (c). Data sources: Naomuhong, Dashiugou, Heihaibei, Xizangdagou after [47]. ADR = Andesite, dacite, and rhyolite field, VAG = volcanic-arc granites, WPG = within plate granites, ORG = oceanic ridge granite, and syn-COLG = syn-collision granite. Figure 6a is modified from [48]; Figure 6b,c are modified from [49].

The S isotopic composition of pyrite in the ore and contemporary granite porphyry is consistent, indicating that the deposit may be derived from porphyry magmatic hydrothermal fluids [18]. The $\delta^{34}S_{V-CDT}$ value of pyrite samples range from 4.9‰ to 6.3‰, which is consistent with other gold deposits in EKOB, including Kunlun River (4.4‰–8.1‰) [50], Haxiyatu (4.63‰–6.3‰) [51], and also overlap with the range of some orogenic gold deposit worldwide, including Callie (4‰–11.5‰) [52] and Kanggur (−1‰–2.5‰) [53]. These values coincide with the source range of magmatic hydrothermal fluid in Wulonggou deposit (Figure 7) [54].

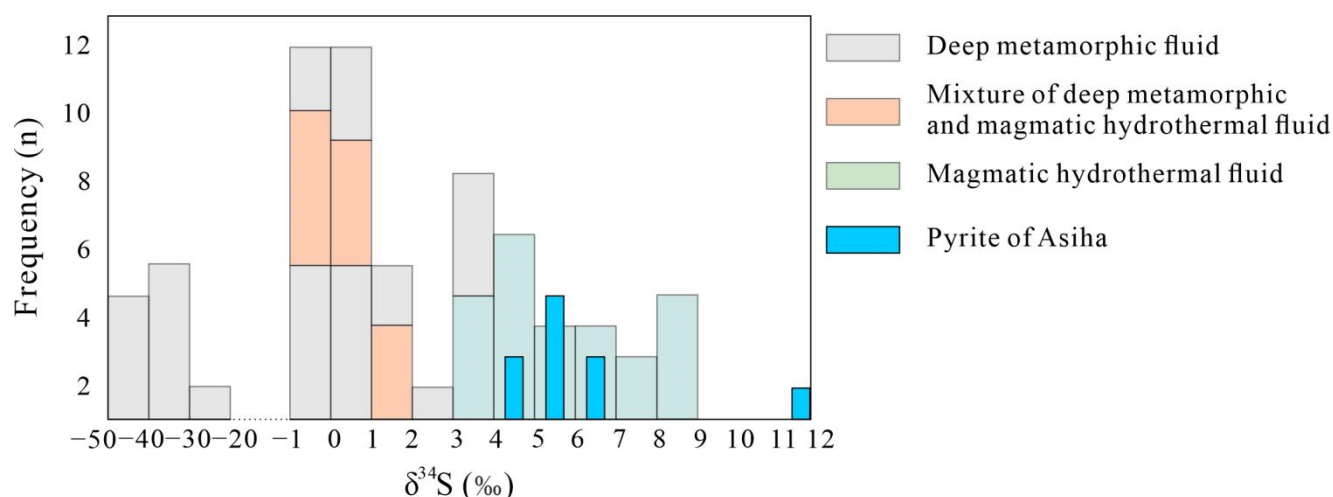


Figure 7. Histogram of sulfur isotopic compositions of pyrite from the Asihā gold deposit, the source of fluid data after Wulonggou deposit [54].

The oxygen isotope of oceanic slab melting magma varies between 6.36‰ and 8.17‰ [55], which is clearly lower than the oxygen isotopic data of Asihā complex (Figure 8a). The high oxygen isotopic composition may reflect that crust or crustal materials were incorporated into the magmatic melt [2,55,56], and the $\delta^{18}\text{O}$ value of ore-bearing granites obviously higher than that of non-ore-bearing granites pluton (Figure 8b). Therefore, the melting of subduction sediments perhaps will produce such adakitic signature. Such a petrogenesis is also consistent with the original petrogenesis of adakite, which is derived from the melting of oceanic basaltic crust [1].

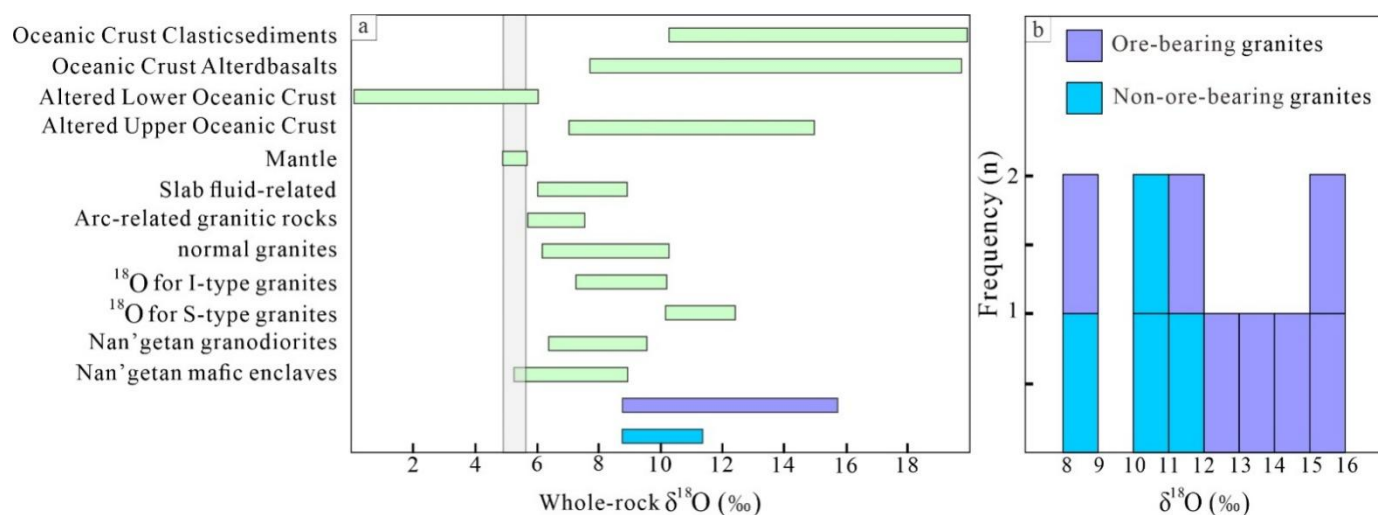


Figure 8. O isotope comparisons of known rock types (a), and isotopic compositions of Asihā complex (b). Data sources: fresh MORB [57], altered upper and lower oceanic crusts [58], arc-related granitic rocks [59], slab fluid-related and arc fractionation trend [55], normal granites, ^{18}O for I-type granites and ^{18}O for S-type granites are taken from [60], Nan'getan granites and MME after [29].

Plate subduction causes high $\delta^{18}\text{O}$ crust material to constantly move into the mantle wedge [37,61]. The range of $\delta^{18}\text{O}$ value of the whole-rock spans the typical I-type ($\delta^{18}\text{O} = 6\text{‰}–10\text{‰}$) and S-type ($\delta^{18}\text{O} = 10\text{‰}–14\text{‰}$, [57]) granites. The accumulation of surface sediments can significantly increase the O isotope of the subduction zone magmatic rocks [62]. Although the Asihā complex has adakitic geochemical characteristics according to the whole rock chemistry, the O isotopic characteristics can still identify the existence of

subducted sediments in the complex. The Pb isotopic compositions of sulfides are relatively uniform. On the $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{208}\text{Pb}/^{204}\text{Pb}$ diagrams, both the pyrite samples and the ore-bearing granitoids plotting well above the Northern Hemisphere Reference Line (Figure 9a). Binary mixing modeling results showed that about ~50%–60% sediment and ~40%–50% mantle or lower crust components (Figure 9b). As mentioned above, the complex was formed during the subduction stage of Paleo-Tethys Ocean. Furthermore, MMEs exist in the quartz diorite samples, which is considered to have originated from the lower crust. Consequently, the Asiha complex may originate from the mixing of subducted oceanic crust with seafloor sediments. Here, we use a loose term “adakite-like” to represent these granites.

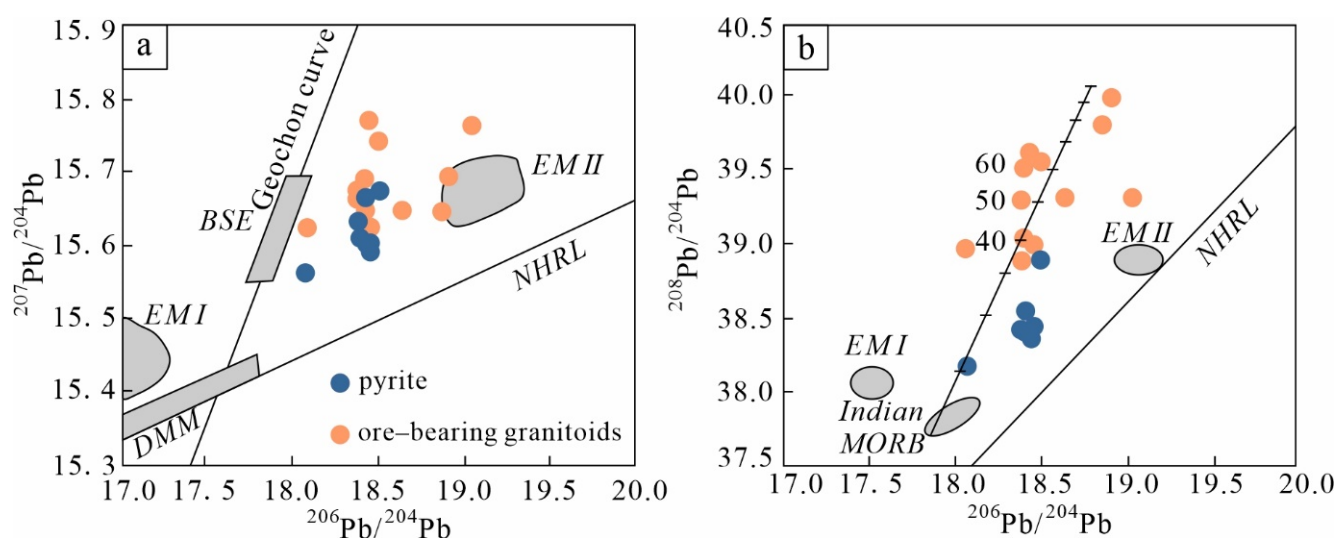


Figure 9. $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ (a) and $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ (b) of sulfides and ore-bearing granitoids from Asiha deposit. Northern Hemisphere Reference Line (NHRL) is from [63]. Mantle source reservoirs BSE, MORB, DMM, EM I and EM II are from [64]. Indian MORB and Pacific MORB are after [65].

5.2. Mineralization Potential of Adakite-like Rocks

Since the late Permian, the Paleo-Tethys Ocean has entered the subduction stage (Figure 10a), and a large amount of magmatic rocks with island arc characteristics are distributed along the EKOB [25,30,36,66]. The intrusive magmatic rocks are rich in Rb, K, Th, U, and LREE and also show the negative of “TNT” (Ta, Nb, Ti) as abnormal. The closure of the Paleo-Tethys Ocean perhaps happened at ~243 Ma [29]. The occurrence of syn-collisional granites (237 Ma) indicates that the subduction stage ended and the intracontinental evolution period started [46] (Figure 10b).

Adakite-like rocks in the subduction island arc environment have high gold mineralization potential [67,68]. A series of adakites in the Philippines were formed by partial melting of the subducted oceanic amphibolite facies during the Cretaceous. Adakite is also the ore-bearing rock intrusion of Machangqing porphyry Cu-Au in Southeastern Tibetan Plateau [69]. With high Cr and Ni concentrations of the olivine or pyroxene, the addition of even a small amount of mantle peridotite to adakitic melts can significantly enhance the Ni-Cr contents [70,71]. Low Ni and Cr contents of Asiha complex indicate that mantle material does not participate in the magmatic evolution on a large scale. Studies have shown that the global distribution of Cenozoic adakite is consistent with that of contemporaneous porphyry deposits, and the ore-forming parent rocks are mostly adakite or adakite-like [72], which are mainly formed by oceanic crustal subduction [1], lower crust delamination [73–75], and subduction of continental crust [76].

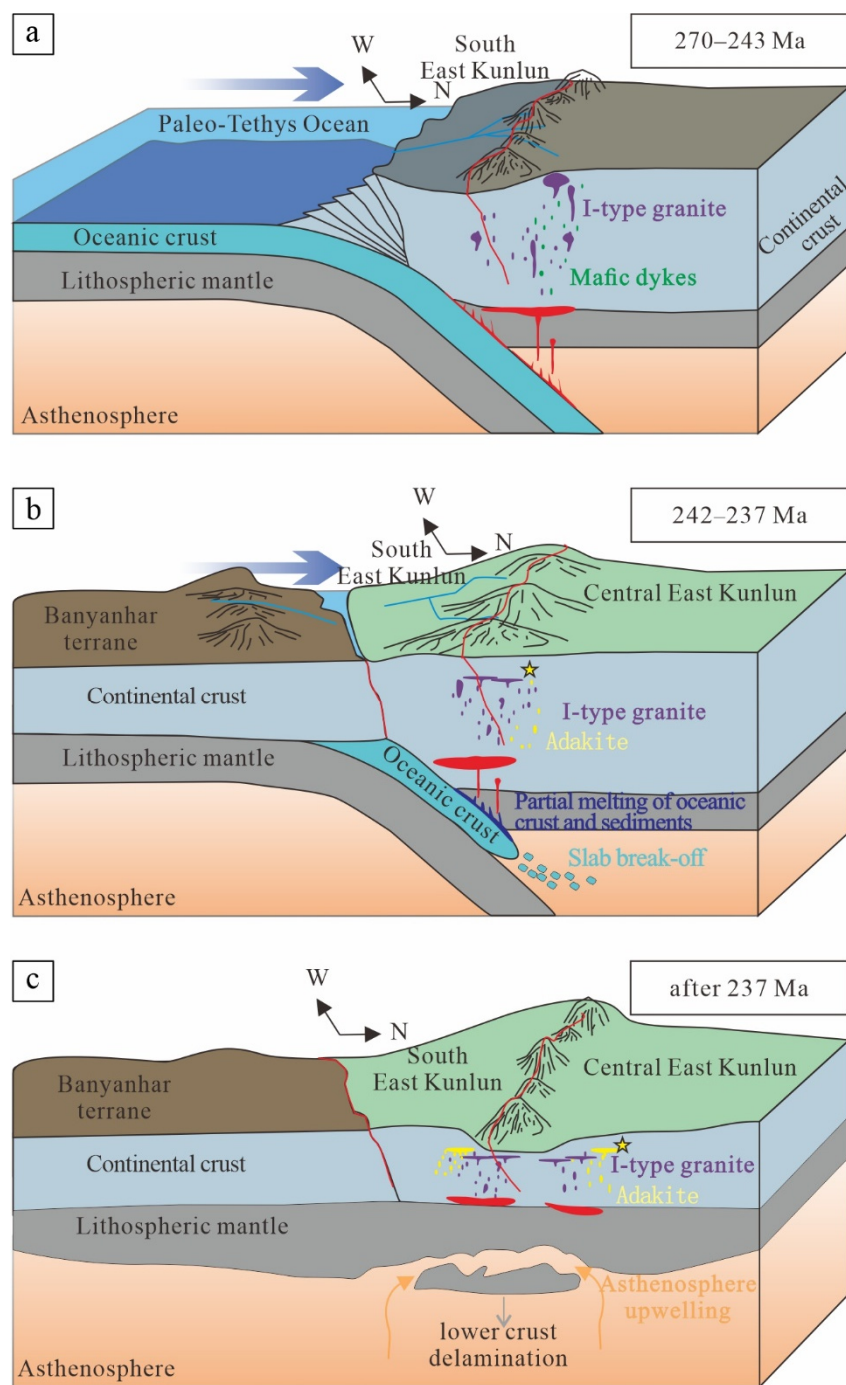


Figure 10. Geological evolution in the EKOB. The Paleo-Tethys Ocean subduction between 270 and 243 Ma (a); the syn-collision stage is between 242 and 237 Ma (b); the post-collision extension setting stage is after 237 Ma (c).

Generally, Au was proposed to be a partition into Cl rich and oxidized aqueous fluids, in the form of chloride complexes, or as moderate salinity liquids containing HS ligands [77,78]. In the magma with low oxygen fugacity, Au is a highly chalcophile element and has strong compatibility with sulfide, and the Au concentration is controlled by sulfide crystallization differentiation during magma evolution [77,79]. The subduction plate melt can carry 10,000 times more Fe_2O_3 than the water fluid into the mantle wedge, which greatly improves the oxygen fugacity of the mantle wedge; this process controls the migration of Au elements in the deep magma [9]. In addition, water-rich magma has higher oxygen fugacity, which is more conducive to adakite mineralization.

The δD and δH_2O values of quartz at the mineralization stage are -117.7‰ – -84.3‰ and 2.7‰ – 9.2‰ , respectively, in the Asiha deposit [33]. The homogenization temperature of gas-liquid fluid inclusions is concentrated at $160\text{--}320\text{ }^{\circ}\text{C}$, and the salinity is concentrated at 38% NaCl. The homogenization temperature of CO_2 -containing three-phase inclusions is concentrated at $300\text{--}420\text{ }^{\circ}\text{C}$, and the salinity is $1.5\text{--}4.5\%$ NaCl, according to Raman analysis; the fluid is a $H_2O\text{--}NaCl\text{--}CO_2\text{--}N_2\text{--}CH_4$ system [33]. Previous research revealed that the Wulonggou gold deposit near the Aisha deposit was formed in the stage of intracontinental evolution of EKOB, and the age of the ore-bearing high magnesium adakite diorite is 215 Ma, with initial $^{87}\text{Sr}/^{86}\text{Sr}(I_{\text{Sr}})$ ratios of 0.709166 to 0.709529, zircon $\epsilon\text{Hf}(t)$ values of -4.9 to -1.0 , and $\epsilon\text{Nd}(t)$ values of -5.7 to -5.1 [32]. The Late Triassic adakite diorite in the Wulonggou deposit was thought to be derived from partial melting mantle peridotite that was metasomatized by the addition of Mesoproterozoic subducted sediment-derived melts [32]. It is reasonable to infer that the Middle Triassic adakite rocks in Asiha perhaps were the result of partial melting of the Paleo-Tethys subducted oceanic crust with seafloor sediments, and the Late Triassic adakite rocks after the collision may be the products of the residual oceanic crust in the subduction zone (Figure 10c). The adakite-like rocks provide the thermal power and hydrothermal solution for gold mineralization and also provides ore-forming materials. They have great potential for gold mineralization and should be regarded as the target for future mineral exploration.

6. Conclusions

Quartz diorite and granite porphyry from the Asiha Au deposit formed at 238.4 ± 1.4 Ma and 240 ± 1.7 Ma, respectively. The geological background of these intrusions is the syn-collision stage of the convergence process of the Paleo-Tethys Ocean. Quartz diorite and granite porphyry have the typical geochemical features of adakite. The Asiha intrusions may be the partial melting of the Paleo-Tethys subducted oceanic crust with seafloor sediments and are markedly different from the traditional adakite. The Asiha deposit is an orogenic gold deposit closely related to adakite-like intrusions. The adakite-like intrusions formed both in Middle Triassic and in Late Triassic in the EKOB have great potential for gold mineralization.

Author Contributions: L.T. and N.N. conceived this contribution. N.N., J.L. and H.K. conducted the field investigation. N.N., J.L. and H.K. performed the zircon U-Pb dating and Lu-Hf isotope analysis. Y.L., Y.X. and N.N. interpreted the data. N.N. and L.T. wrote the original draft of the paper. Q.J. reviewed the original draft of the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the National Science Foundation of Shaanxi Province of China (Grant No. 2023-JC-QN-0359); China Geological Survey (Grant Nos. DD20160013, 121201011000150005-17); State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, CAS (Grant No. SKLLQG2023).

Data Availability Statement: Not applicable.

Acknowledgments: Many thanks are expressed to the anonymous reviewers for their constructive criticism and suggestions on an earlier draft of the manuscript.

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

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