

Article

Neoproterozoic Aksu Diabase Dyke, Chinese South Tianshan: Magma Sources and Implications for Regional Gold Metallogeny

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Abstract: Tianshan is one of the world's largest gold provinces; however, the relationship between gold mineralization and metasomatized subcontinental lithospheric mantle (SCLM) remains poorly understood. To improve our understanding, we present new bulk-rock geochemistry and platinum group element (PGE) concentrations of the SCLM-sourced Aksu Neoproterozoic diabase dykes in Chinese South Tianshan. These data, combined with in situ laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) analyses of hydrothermal pyrite grains in the diabase dykes, are used to discuss the SCLM source characteristics in the region and their potential links to formation of gold deposits. The diabase dykes exhibit high Th/Yb (0.47–0.62) and low Nb/U (13.4–16.3) ratios, indicating that magma evolution involves subduction-related fluid metasomatism and limited contamination of the continental crust. This is consistent with little variation in whole-rock Pd/Zr, Cu/Zr, and Ni/MgO ratios, suggesting that no sulfide segregation was caused by crustal contamination and magma mixing. In addition, the diabase dykes show low PGE and Au contents, with high Cu/Pd ($>10^5$) and low Cu/Zr (<0.5) ratios, indicating that magmas were derived from low-degree partial melting of the SCLM under S-saturated conditions. Such source characteristics indicate residual sulfides and chalcophile elements (e.g., PGEs, Au, and Cu) were concentrated at the SCLM reservoir in South Tianshan. Hydrothermal pyrite in the studied dykes has similar Au/Ag ratios and trace element distribution patterns to gold-bearing pyrite of lode gold deposits in Chinese South Tianshan, indicating that metasomatized SCLM may have contributed ore metals during the formation of these gold deposits. Adding to the available data, our study highlights that the SCLM may be a potential metal source reservoir, and it may have contributed to formation of the lode gold deposits in Chinese South Tianshan.

Keywords: diabase dykes; sub-continental lithospheric mantle; lode gold deposit; metal source; Chinese South Tianshan



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1. Introduction

The relationship between subcontinental lithospheric mantle (SCLM) and formation of gold metallogenic provinces has received considerable attention in the last 20 years [1–3]. For instance, the SCLM has been suggested to be a prominent source in some major gold provinces, such as Jiaodong [4,5], Deseado Massif [6], and the western margin of Yangtze Craton [7]. However, there are also major gold provinces that are thought to be unrelated to the SCLM, e.g., Yilgarn Block [8], Central Victoria [9], Lena [10,11], Otago Schist [12,13], and the Abitibi greenstone belt [14].

Tianshan is one of the world's largest gold provinces and hosts an array of world-class lode gold deposits, e.g., Muruntau, Kumtor, and Unkurtash [15–17]. However, the relationship between formation of these gold deposits and metasomatized subcontinental lithospheric mantle (SCLM) remains poorly understood [18]. Mantle-derived components have been recognized in ore-forming fluids of the giant Muruntau gold deposit based on low radiogenic initial Os isotope ratios of auriferous arsenopyrite and elevated $^3\text{He}/^4\text{He}$ ratios

of fluid inclusion in gold-bearing quartz [19,20]. Moreover, Mao et al. (2004) confirmed comparable ca. 296–298 Ma ages for gold ores and alkalic granitoids at the Kumtor gold deposit, indicating a mantle-related source [21]. Conversely, Wall et al. (2004) argued that mantle-related magmatic rocks have no genetic links with gold deposits, but instead provided magmatic heat to generate gold-bearing metamorphic fluids (TAG model) [22,23]. Uncertainty about a metal source derived from mantle also concerns lode gold deposits in the Chinese part of Tianshan, e.g., the partial mantle-related C–H–O isotopic characteristics of the Sawayaerdun gold deposit [24]. These controversies are largely due to relatively poor exposure of SCLM-derived rocks in the region, and limited attention has been paid to their relationship with the formation of gold deposits.

The Neoproterozoic Aksu diabase dykes (ca. 760–745 Ma) occur sporadically in southwestern Chinese Tianshan and are thought to be derived from a metasomatized SCLM source [25]. Contemporaneous lode gold deposit, i.e., Djamgyr gold deposit (ca. 802 Ma), has also been reported elsewhere in Kyrgyzstan’s Tianshan [26]. In the Chinese part of Tianshan, although the Aksu diabase dykes formed several hundred million years earlier than the regional Au mineralization (ca. 280–290 Ma [16,20]), host rocks of these diabase dykes also host the Awanda lode gold deposit, which represents the second-largest gold deposit in the region [27]. The potential link between these dykes and regional gold metallogeny requires further evaluation.

In this study, we report new whole-rock geochemical and PGE data on the Aksu diabase dykes, as well as in situ LA-ICP-MS trace element analyses of pyrite grains in the Aksu diabase dykes. Based on the findings, we discuss the SCLM source characteristics in the Chinese Tianshan region and their potential links to large-scale gold mineralization. Adding to the available data, we advance the current understanding of the metal sources of the lode gold deposits in the Tianshan gold province.

2. Geological Setting

The Tianshan orogen in the southwestern part of the Central Asian Orogenic Belt (CAOB; Figure 1a) extends from the Kyzylkum Desert in western Uzbekistan, through Tajikistan and Kyrgyzstan, to Xinjiang in NW China (Figure 1b) [28]. The Chinese part of the Tianshan orogen has been subdivided into four major suture-bounded tectonic domains from north to south, namely Chinese North Tianshan, the Kazakhstan–Yili Block, the Middle Tianshan Block, and South Tianshan (Figure 1b) [29].

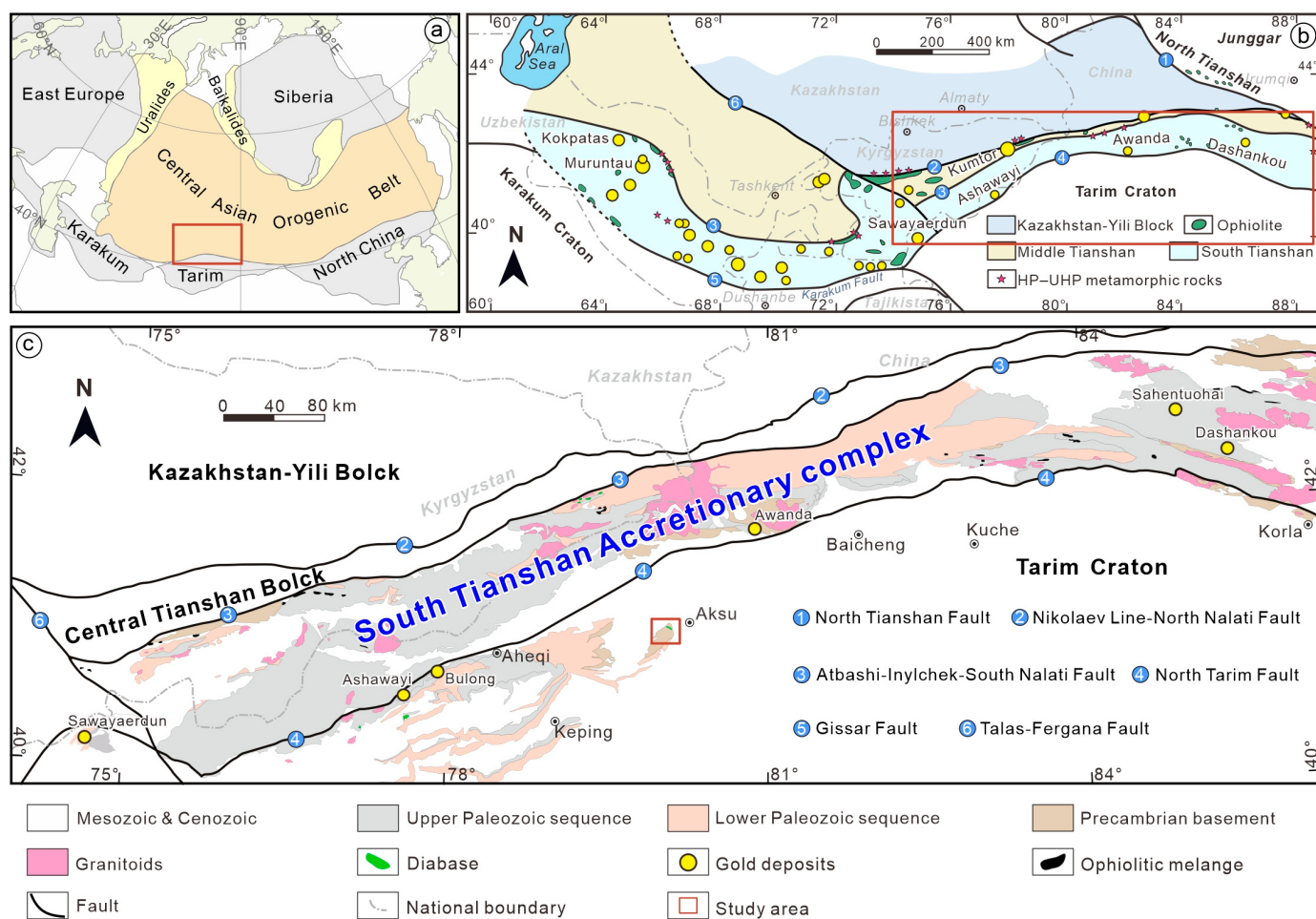


Figure 1. (a) Tectonic location of the Tianshan orogen in the Central Asian Orogenic Belt. (b) Simplified geological map of Tianshan showing the locations of major lode gold deposits (modified from [16]). (c) Geological map of Chinese South Tianshan showing the location of the Aksu terrane (modified from [30]).

South Tianshan, hosting major lode gold deposits, represents a late Paleozoic accretionary complex bounded by the North Tarim Fault to the south and the Atbashi–Inylchek–South Nalati Fault to the north (Figure 1c) [29]. It is composed of a series of dismembered Precambrian terranes that are overlain by Paleozoic meta-sedimentary sequences [28]. The Precambrian terranes are composed mainly of the Paleoproterozoic Xinditagh Group, and the Neoproterozoic Aksu Group, and they are all exposed in the southernmost part of Chinese South Tianshan. The Lower Paleozoic strata are mainly exposed in the middle part of South Tianshan (Figure 1b) and are composed of Lower Cambrian to Ordovician passive margin sediments and Upper Silurian clastic sedimentary sequences [31,32]. Upper Paleozoic strata occur extensively across South Tianshan (Figure 1c) and mainly consist of Devonian to Carboniferous clastic sedimentary rocks, including carbonaceous rocks, calcareous siltstone, grey siltstone, marine carbonate rocks, sandstone, calcareous sandstone, and shale [31]. The Upper Silurian to Carboniferous metasedimentary formations are the most important gold-hosting sequences in Chinese South Tianshan (Figure 1c) [15,33]. Permian fluvial sediments and rift-type volcanic rocks are tightly overlain by the Pre-Carboniferous strata [34].

A few outcrops of Neoproterozoic mafic and voluminous Early Permian A-type granites and basalts are exposed in Chinese South Tianshan (Figure 1c). The Neoproterozoic mafic dykes cross-cut the Neoproterozoic Aksu Group, cropping out mainly in the southwestern part of Aksu city (Figure 2). The Early Permian (ca. 290–280 Ma) A-type granitoids

are widespread across South Tianshan and show both A1 and A2 affinities, which have been interpreted to be related to the Tarim mantle plume [35] or formed in a post-collisional extension setting [36]. Basaltic lavas and mafic–ultramafic complexes (295–285 Ma) are exposed in the southernmost part of Chinese South Tianshan, e.g., the Keping and Bachu areas. These rocks show oceanic island-arc basalt (OIB)-like features, and are accepted to be related to the Permian Tarim mantle plume [37,38].

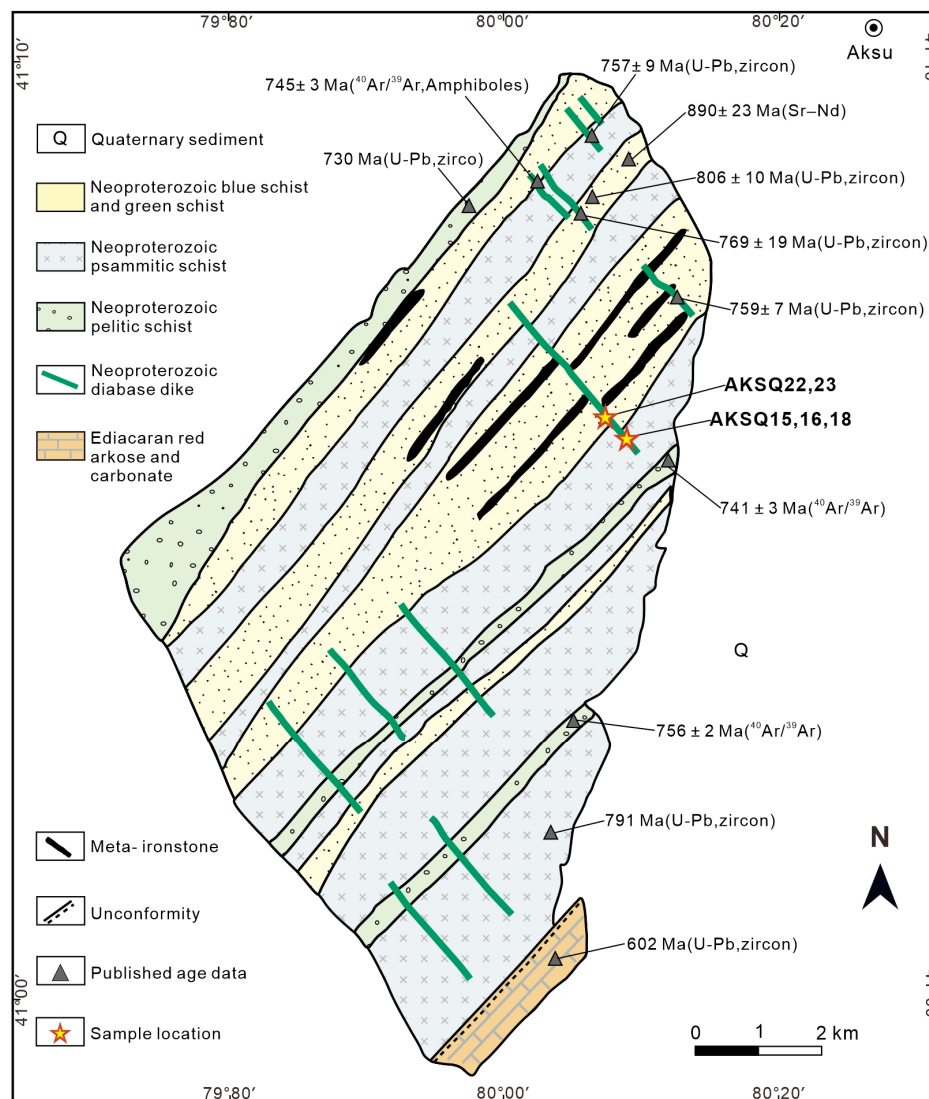


Figure 2. Simplified geological maps of the Aksu terrane with locations of samples (modified from [39,40]), as well as published ages for the diabase dykes and Precambrian schist [39–44].

The Aksu district is localized in the southwestern part of Chinese South Tianshan (Figure 1c). The Precambrian basement belts are composed mainly of the Neoproterozoic Aksu Group and Ediacaran Sugetbrak Formation [41]. The Aksu Group is mainly exposed in southwestern Aksu (Figure 2), including greenschist, blueschist, psammitic schist, pelitic schist, and metagreywacke [39,42]. The blueschist protolith has been dated to be of ca. 806–754 Ma based on whole-rock $^{40}\text{Ar}/^{39}\text{Ar}$ and detrital zircon U–Pb dating methods [39,40]. The pelitic schist has a $^{40}\text{Ar}/^{39}\text{Ar}$ age of 756–741 Ma [43] or detrital zircon U–Pb age of 730 Ma [42]. The psammitic schist has a detrital zircon U–Pb age of ca. 791 Ma [43]. The deformed sequence of the Aksu Group is crosscut by a series of NW-striking diabase dykes (Figures 2 and 3a), which have U–Pb zircon ages of 759 ± 7 Ma (SHRIMP; [27]) and 757 ± 9 Ma (LA–ICP–MS; [44]). In addition, amphibole from the mafic

dyke yielded a $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 744.5 ± 2.8 Ma [41]. These different ages indicate that the crystallization age of the Aksu diabase dyke is most probably Neoproterozoic (~760–745 Ma; [45]). In addition, these diabase dykes show an enrichment of large-ion lithophile element (LILE) and light rare-earth element (LREE), along with depletion of high-field-strength element (HFSE) and heavy rare-earth element (HREE), which are similar to arc-like geochemical signatures [27]. The large range of radiogenic $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ from 0.7050 to 0.7074, and $^{143}\text{Nd}/^{144}\text{Nd}$ with initial $\epsilon\text{Nd}_{(t)}$ values ranging from -6.4 to 1.5 , further indicate that they might have been derived from a metasomatized SCLM source [27,45].

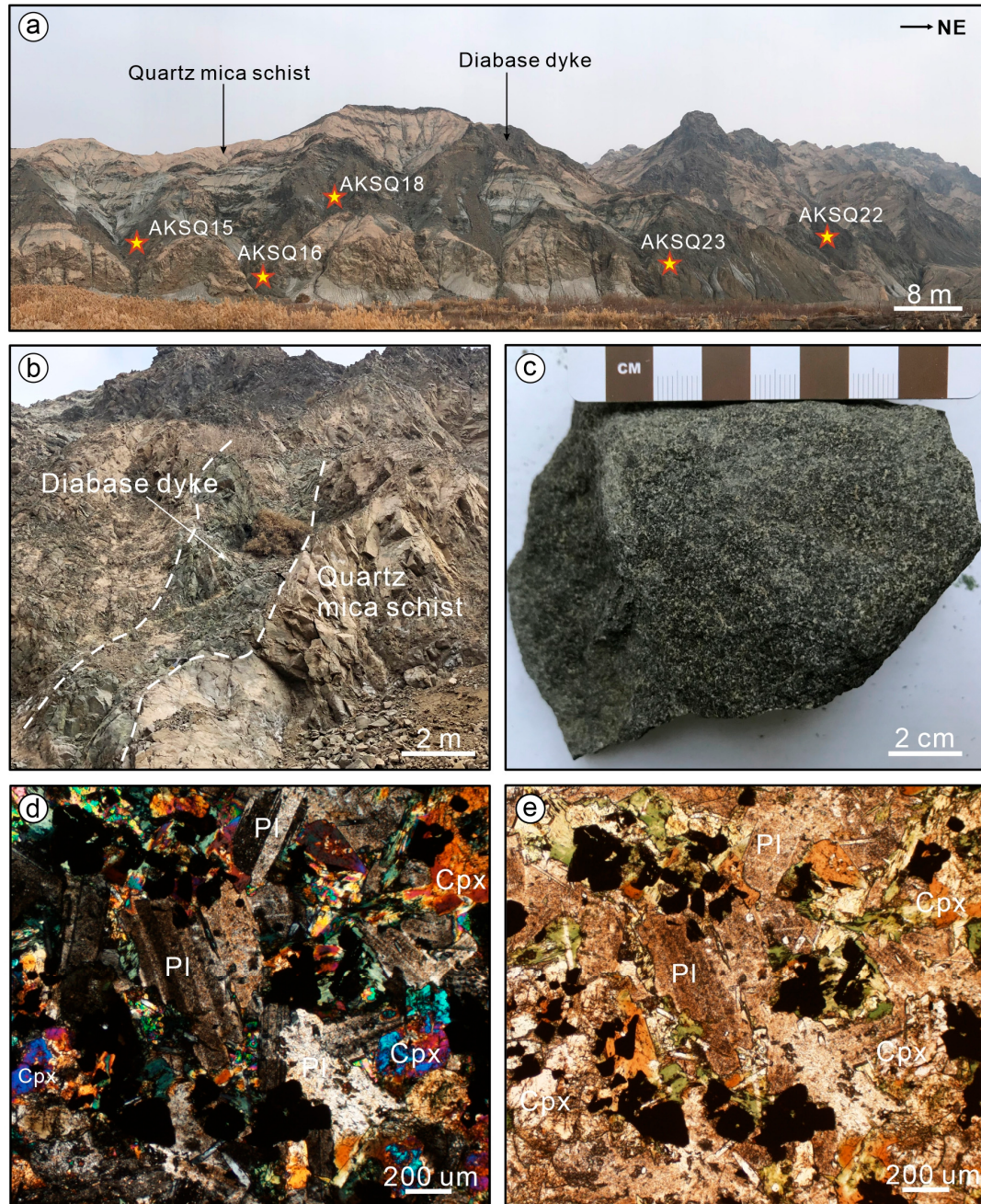


Figure 3. Photographs and photomicrographs showing the occurrence and mineralogy of the diabase dykes in the Aksu area. (a,b) Neoproterozoic diabase dykes intruding the deformed Neoproterozoic Aksu Group; (c) hand specimen of the Aksu Neoproterozoic diabase; (d,e) photomicrograph of diabase showing the mineral assemblage of the diabase under cross-polarized light. Abbreviations: Pl = plagioclase, Cpx = clinopyroxene.

3. Field Geology and Sample Description

Field investigation and sample collection focused on the SCLM-derived Neoproterozoic diabase dykes in southwestern Aksu (Figures 1b and 2). The diabase dykes have NW–SE strikes with variable extended widths ranging from 2 to 10 m (Figures 2 and 3a–c), intruding into quartz mica schist and chlorite schist of the Neoproterozoic Aksu Group (Figure 3a–c). Five fresh diabase samples were collected from the Aksu diabase dykes (Figures 2 and 3a,d). The collected diabase samples were greyish-green in color and free of alteration (Figure 3e). They were composed of plagioclase (50–60%), clinopyroxene (30–35%), and hornblende (5–10%), with some magnetite and pyrite (Figure 3f). Sampling coordinates and petrological descriptions of the diabase samples are given in Table 1.

Table 1. Major oxide (wt.%) and trace element (ppm) compositions of the Aksu Neoproterozoic diabase dykes, Chinese South Tianshan.

Sample	AKSQ-15	AKSQ-16	AKSQ-18	AKSQ-22	AKSQ-23
Coordinates	N41°10′05″ E80°03′40″	N41°10′07″ E80°03′37″	N41°10′08″ E80°03′36″	N41°10′11″ E80°03′36″	N41°10′10″ E80°03′39″
SiO ₂	48.01	47.26	47.38	48.1	47.81
TiO ₂	2.775	2.801	2.803	2.761	2.811
Al ₂ O ₃	14.02	13.87	13.95	14.05	13.93
TFe ₂ O ₃	14.3	14.53	14.54	14.29	14.57
MnO	0.242	0.233	0.233	0.237	0.234
MgO	4.78	4.88	4.89	4.76	4.85
CaO	7.8	8.23	8.08	7.63	7.83
Na ₂ O	3.53	3.84	3.45	3.56	3.49
K ₂ O	1.55	1.32	1.66	1.67	1.53
P ₂ O ₅	0.943	0.946	0.902	0.95	0.925
LOI	1.53	1.74	1.87	1.82	1.85
Mg#	39.84	39.85	39.99	39.76	39.74
Total	99.72	99.92	100.01	100.03	100.03
Sc	29.5	29.6	32.5	32	32.3
V	366	366	224	214	231
Cr	22	22.6	22.1	20.8	23
Co	57.3	55	48	46.8	45
Ni	21.6	22.4	22.6	20.9	21.7
Cu	41.1	41.6	38	36.2	37.6
Zn	155	151	129	131	128
Ga	21.6	21.3	20.5	20.3	20.7
Rb	45.6	33.2	28.4	28.6	26.9
Sr	489	548	447	355	377
Y	38.4	37.2	37.4	38.3	38.3
Zr	160	144	146	152	156
Nb	5.9	5.58	5.48	5.7	5.86
Cs	0.447	0.373	0.398	0.401	0.422
Ba	1691	1864	1736	1708	1709
La	33.6	32	28.1	29.2	28.6
Ce	72.6	68.9	59.7	64.1	54
Pr	9.35	8.95	8.22	8.56	8.6
Nd	44.7	42.9	38	40	38.9
Sm	10	9.68	8.56	8.98	8.77
Eu	3.96	3.89	3.67	3.84	3.82
Gd	9.32	9.07	8.85	9.18	8.99
Tb	1.37	1.35	1.22	1.28	1.29
Dy	8.47	8.25	7.41	7.64	7.71
Ho	1.68	1.63	1.47	1.54	1.51
Er	4.43	4.23	3.78	3.95	3.96
Tm	0.617	0.592	0.527	0.548	0.552
Yb	3.79	3.68	3.25	3.35	3.38
Lu	0.565	0.543	0.472	0.489	0.489
Hf	4.85	4.5	3.65	3.92	3.95
Ta	0.461	0.431	0.349	0.371	0.37
Pb	6.49	5.98	4.34	4.13	4.2
Th	2.35	2.15	1.54	1.64	1.68
U	0.44	0.394	0.335	0.377	0.377
Eu/Eu*	1.24	1.25	1.28	1.28	1.31

Notes: Total iron as TFe₂O₃; TFeO = TFe₂O₃ × 0.8998; Mg# = MgO/(MgO + TFeO) × 100 in atomic ratio; REE—rare earth elements; LOI = loss on ignition; Eu/Eu* = 2 × EuN/(SmN + GdN), subscript "N" denotes normalization to chondrites (Sun and McDonough, 1989 [46]).

A large amount of subhedral pyrite grain was found in our diabase samples (Figure 4). Pyrite occurs as an interstitial phase in plagioclase and clinopyroxene (Figure 4), and it is irregular in shape and porous (100–300 μm), suggesting a hydrothermal origin.

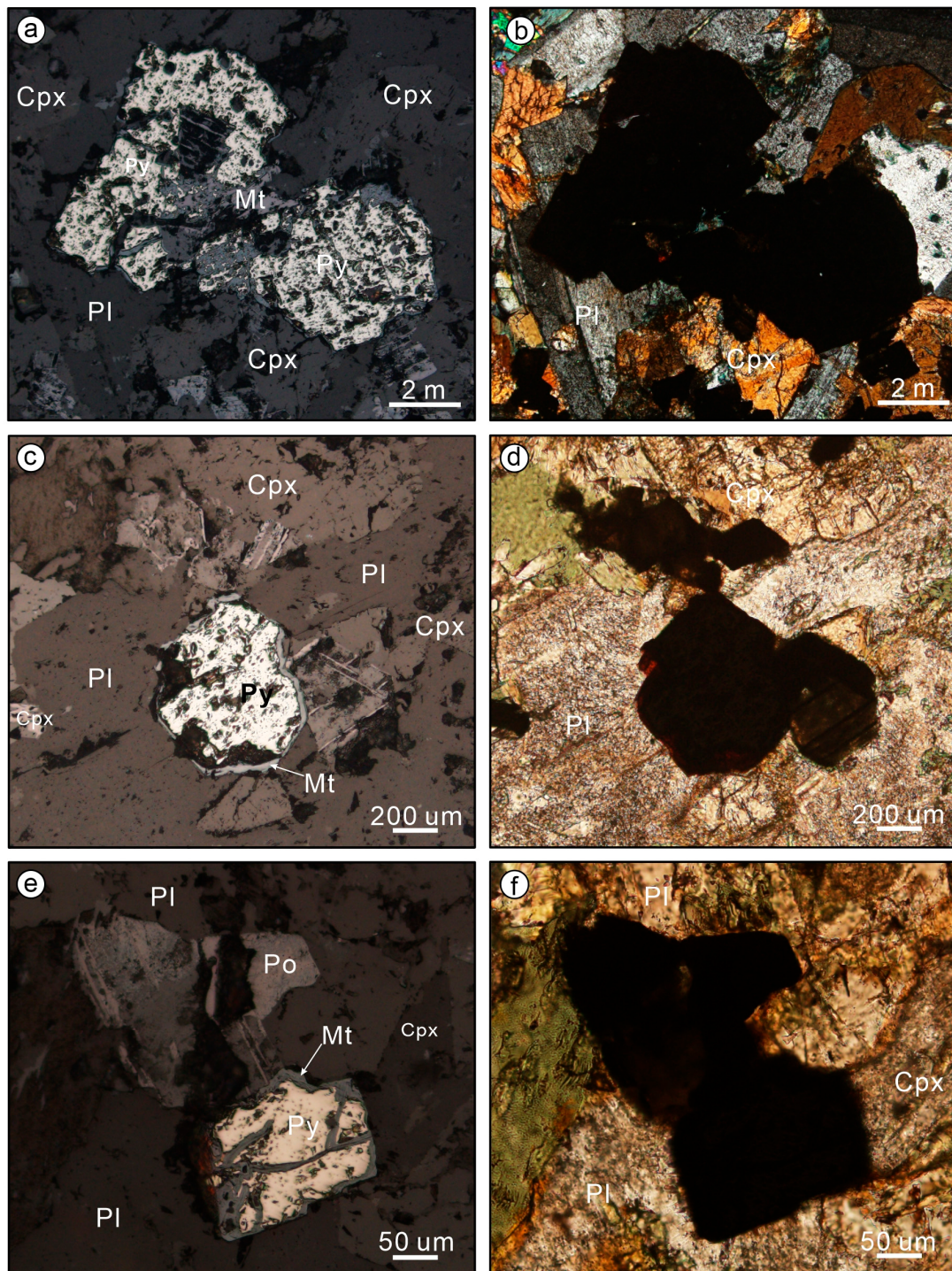


Figure 4. Photomicrographs showing the sulfide phases in the diabase dykes of the Aksu area. (a,b) Pyrite grains are generally intergrown with magnetite and silicates in plagioclase and clinopyroxene; (c,d) subhedral pyrite grains enveloped by magnetite rims; (e,f) pyrrhotite, pyrite, and magnetite within plagioclase of the diabase dykes. Abbreviations: Pl = plagioclase, Cpx = clinopyroxene, Py = pyrite, Po = pyrrhotite, Mt = magnetite.

Pyrite grains are generally intergrown with magnetite and silicate minerals, and a few of them contain magnetite rims (Figure 4c,d), suggesting dissolution of sulfide melt by a volatile phase. The textural relations among pyrrhotite, pyrite, and magnetite suggest a significant associated transfer of sulfur and chalcophile metals such as Cu and Au to hydrothermal fluids (Figure 4e,f) [47].

4. Analytical Methods

4.1. Whole-Rock Major and Trace Elements

Five fresh Neoproterozoic diabase samples lacking signs of alteration or wall-rock assimilation were crushed in an agate mill to a powder of 200 mesh size, and they were selected for whole-rock major and trace element analyses at the Institute of Geochemistry, Chinese Academy of Sciences (IGCAS). Before the analyses, all samples were inspected using a general magnifier to select only fresh surface devoid of any weathering (alteration). Major elements were determined by X-ray fluorescence spectrometry (ARL Perform' X4200) methods. Analytical uncertainties were <5% for major elements. Trace elements were analyzed using inductively coupled plasma mass spectrometry (ICP-MS) (Plasmaquant MS elite), with analytical uncertainties below 10%. The analytical protocol was similar to that described in [48].

4.2. Whole-Rock PGE Elements

Four samples of Neoproterozoic diabase were analyzed for their platinum group element (PGE; Pt, Pd, Ru, Rh, and Ir) geochemistry at the IGCAS. The PGE elements were determined by the isotopic dilution method coupled with ICP-MS (Plasma Quant ®MS) analysis. Pt, Pd, Ru, and Ir were determined by isotopic dilution, and ¹⁹⁴Pt was used as an internal standard for calculating the abundance of the single isotope element Rh. Detailed analytical procedures are described in [49]. The total procedural blanks were lower than 0.0101 ng/g for Pd, 0.0132 ng/g for Ru, 0.0012 ng/g for Os, 0.0053 ng/g for Ir, 0.0019 ng/g for Pt, and 0.0021 ng/g for Rh. Reference standards of TDB-1 (diabase) were used to monitor the accuracy, which was above 90%.

4.3. In Situ LA-ICP-MS of Elements

In situ trace element concentrations of pyrite from the diabase samples were determined using LA-ICP-MS (Coherent, Germany) at the IGCAS. The analytical instrumentation was a Coherent Compex-Pro 193 nm ArF (Coherent, Germany) excimer laser ablation system attached to an Agilent 7700x ICP-MS (Agilent, USA). The operating condition and analytical procedure applied to sulfide were described in [50]. Spot ablation was carried out using a size of 26 µm at 3 J/cm² and a 5 Hz repetition rate. Each analysis comprised a background acquisition of 30 s (gas blank) and a 60 s analysis of the sample. The integrated count data to concentrations for lithophile elements were calibrated and converted by GSD-1G. Sulfide reference material MASS-1 was analyzed as an unknown sample to check the analytical accuracy [51]. The background and analysis signals comprised off-line selection and integration by Excel-based software IC-PMS DataCal (version 6.37), along with time-drift correction and quantitative calibration for trace element analysis [52]. Concentration data and detection limit calculations were performed following the protocol in [53].

5. Results

5.1. Whole-Rock Major and Trace Elements

Whole-rock major and trace element compositions of the diabase samples are listed in Table 1. The Aksu diabase samples possess low loss on ignition (LOI) values ranging from 1.53 to 1.87 wt%. The samples have low SiO₂ (47.26–48.1 wt%) and K₂O + Na₂O (5.02–5.23 wt%) values, mostly plot within the alkaline series field of a TAS diagram (Figure 5a), and exhibit sub-alkaline characteristics on a Nb/Y vs. Zr/TiO₂ plot (Figure 5b). The Aksu Neoproterozoic diabase samples exhibit high (La/Yb)_N (2.01–6.03) ratios, and they display enrichment of LREE with flat HREE (Figure 6a). In primitive mantle-normalized diagrams, the diabase samples are enriched in large-ion lithophile elements (LILE) such as Rb, Ba, and Th, and depleted in HFSEs, with remarkable negative Nb and Ta anomalies (Figure 6b).

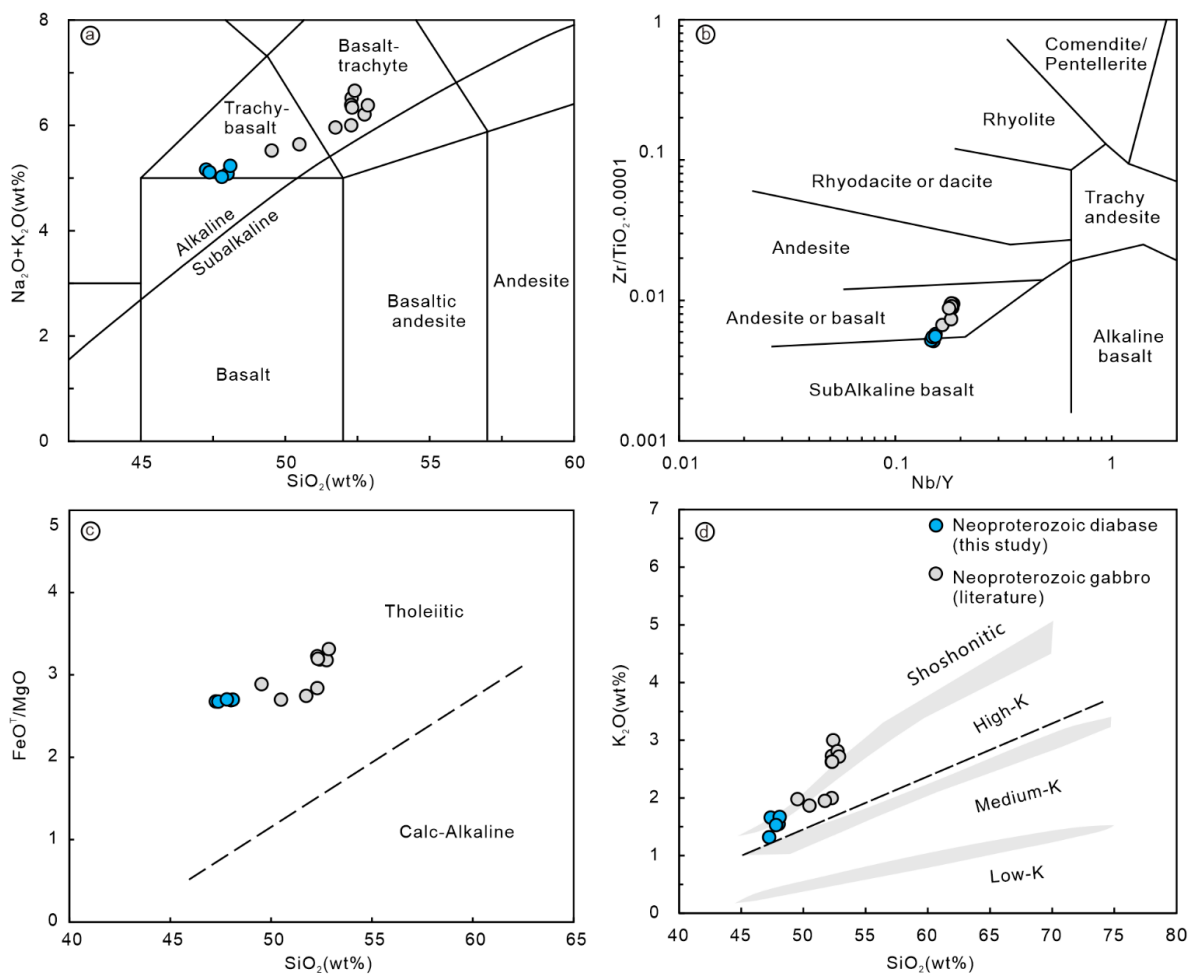


Figure 5. Rock classification diagrams. (a) Total alkali versus silica (TAS) diagram (from [54]). (b) Nb/Y versus Zr/Ti diagram (modified from [55]). (c) SiO_2 versus FeO_T/MgO plot [56]. (d) K_2O versus silica diagram [57]. Data sources: Neoproterozoic gabbro [27,45]. Data can be found in Supplementary Table S1.

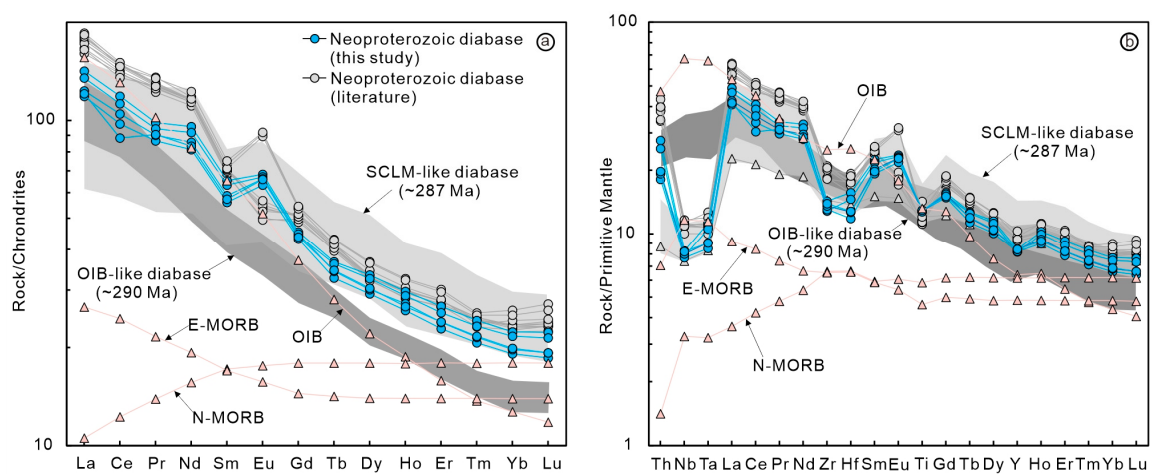


Figure 6. Chondrite-normalized REE patterns (a) and primitive mantle-normalized multiple-trace-element diagrams (b) for Aksu Neoproterozoic diabase dykes. Data sources: N-MORB; E-MORB; OIB values are from [27,45]; and 287 Ma sub-continental lithospheric mantle (SCLM)-like diabase and 290 Ma ocean island-arc basalt (OIB)-like diabase in the Aksu area are from [38]. Literature data are compiled in Supplementary Table S2.

5.2. Whole-Rock PGE Contents

Whole-rock platinum group element (PGEs) results are listed in Table 2. The Aksu Neoproterozoic diabase exhibits low PGE contents ($\Sigma\text{PGEs} = 0.36\text{--}0.65$ ppb), with Pt at 0.02–0.23 ppb, Pd at 0.04–0.44 ppb, Ir at 0.02–0.12 ppb, Ru at 0.21–1.41 ppb, and Rh at 0.24–1.45 ppb. The primitive mantle-normalized PGE patterns are roughly horizontal for the Aksu diabase, with an anomalous trough at Pt and peaks at Rh and Pd (Figure 7a). They are markedly contrasted with PGE patterns of regional mafic dykes (Zhengyuan and Yilgarn Craton lamprophyres), Victoria gabbro (Figure 7b [58–60]), and felsic intrusions (Tuwu porphyry Cu deposits, Figure 7b, [61]). In addition, the sloped patterns of diabase are different from those of orogenic Au deposit (Figure 7a) [5] and porphyry Cu–Au (PGE) deposit (Figure 7b) [62].

Table 2. PGE, Cu, Ni, and S concentrations in the Aksu diabase dykes, Chinese South Tianshan.

Sample No.	Pt (ppb)	Pd (ppb)	Ir (ppb)	Ru (ppb)	Rh (ppb)	ΣPGE (ppb)	Au (ppb)	Cu (ppm)	S (ppm)	Ru/Ir	Ru/Pt	Pd/Ir	Pd/Pt
AKSQ-15	0.064	0.182	0.008	0.097	0.011	0.362	<1	41.1	2446	12.30	1.52	22.75	2.85
AKSQ-16	0.071	0.373	0.008	0.091	0.014	0.5573	<1	41.6	2735	10.95	1.28	46.62	5.27
AKSQ-18	0.020	0.275	0.015	0.142	0.090	0.5425	<1	38	2560	9.23	7.11	18.33	13.75
AKSQ-22	nd	0.243	0.008	0.132	0.011	0.3942	<1	36.2	2022	15.92	13.21	30.37	24.26
AKSQ-23	0.313	0.219	0.007	0.104	0.010	0.6529	<1	37.6	1955	15.46	0.33	31.29	0.70
TDB-1, obtained	4.672	22.059	0.044	0.411	0.661	—	—	—	—	—	—	—	—
Primitive mantle *	7.1	3.9	3.2	5.0	0.9	—	—	—	—	—	—	—	—

* Primitive mantle values are from [46]. “nd” means the content is below the minimum detection limit.

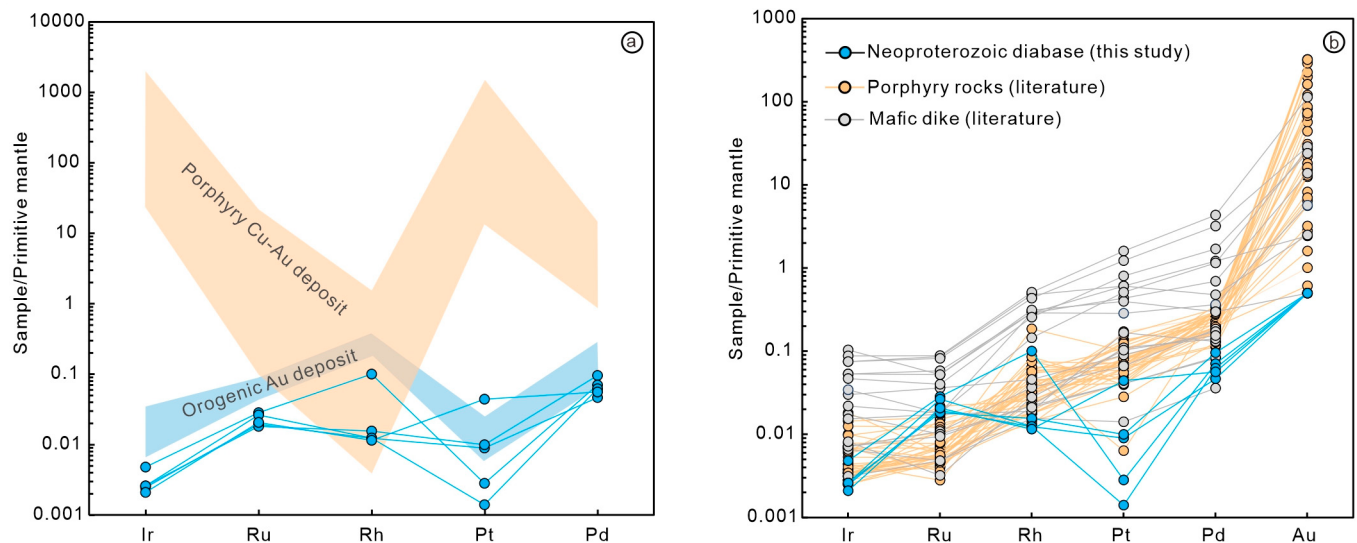


Figure 7. Primitive mantle-normalized PGE and Au contents for the Aksu Neoproterozoic diabase dykes. Data sources: Danba gold deposit [3], Porphyry Cu–Au deposits [62], Zhengyuan lamprophyres [59], Victoria gabbro [58], Yilgarn Craton lamprophyres [60], and Tuwu felsic intrusions [61]. Literature data are compiled in Supplementary Table S2.

5.3. In Situ LA-ICP-MS of Elements

In situ LA-ICP-MS element compositions are listed in Supplementary Table S3. Only 12 of the 28 spot analyses revealed detectable gold. The gold content in pyrite varied from below the detection limit to 0.34 ppm with a mean of 0.04 ppm, while arsenic varied from 12.54 to 603 ppm (mean=244 ppm). The Au/Ag ratios of pyrite from the Aksu Neoproterozoic diabase were between 0.01 and 0.1 (Figure 8). Moreover, these pyrite grains were rich in a host of elements such as As, Bi, Co, Mn, Ni, Sb, Pb, and Ti (Figure 9).

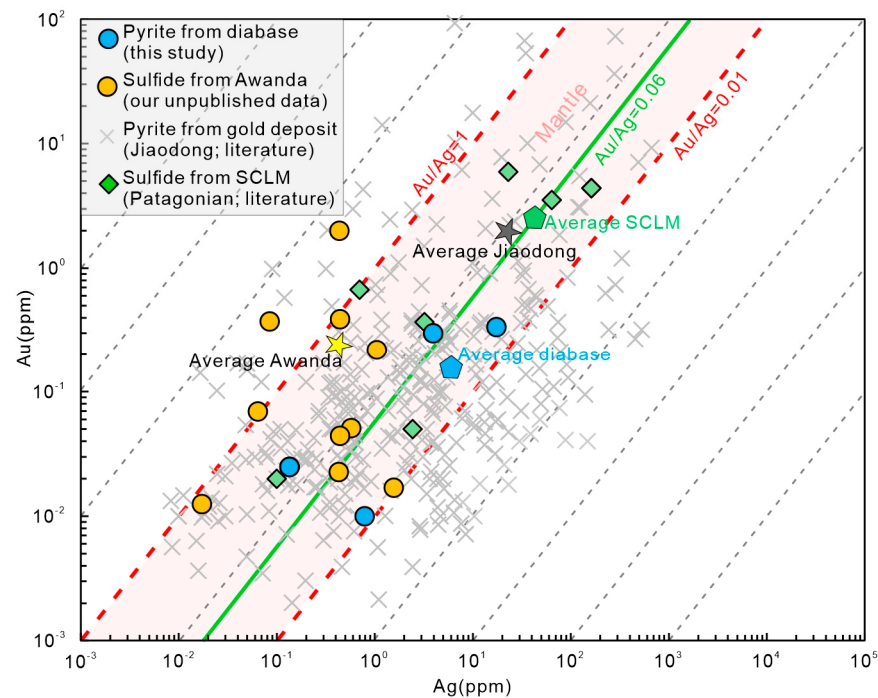


Figure 8. Au versus Ag contents of pyrite from the Aksu Neoproterozoic diabase dykes and lode gold deposits in Chinese South Tianshan. Dotted lines are constant Au/Ag ratios. Data sources: mantle sulfides [6]; Jiaodong gold deposits [63–70]; Awanda gold deposits (our unpublished data). Literature data are compiled in Supplementary Table S4.

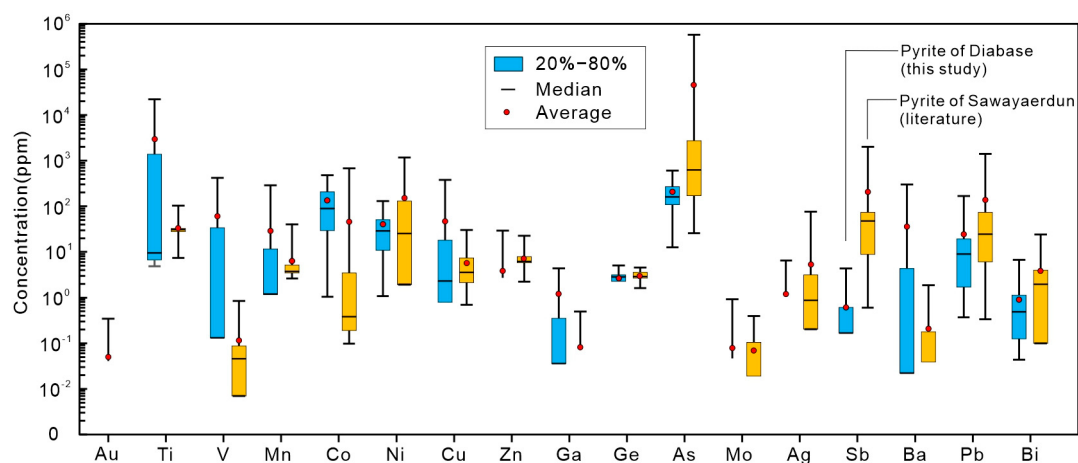


Figure 9. Trace element concentration of pyrite from the Aksu Neoproterozoic diabase dykes and Sawayaerdun gold deposit in Chinese South Tianshan. Data source: Sawayaerdun gold deposit [71].

6. Discussion

6.1. Metasomatized SCLM Source for the Aksu Diabase

The Aksu diabase dykes show low LOI values (1.53–1.87 wt%), suggesting that these dykes were largely unaffected by post-magmatic alteration. The Aksu diabase dykes have limited variation in Th contents (1.54–2.35 ppm) and show no correlation between Nb/La and Nb/Th ratios (Figure 10a), suggesting that crustal contamination had limited effect on their composition during magma ascension. In addition, these diabase samples have higher Ba (1708–1864 ppm) and Sr (355–548 ppm) contents than the average continental crust (Ba = 390 ppm, Sr = 325 ppm; [72]), further suggesting that the potential influence of crustal contamination can be excluded. This is also supported by the low radiogenic Pb isotopic compositions of these diabase dykes ($^{206}\text{Pb}/^{204}\text{Pb}$: 16.54 ~ 16.92, $^{207}\text{Pb}/^{204}\text{Pb}$: 15.32 ~ 15.40, $^{208}\text{Pb}/^{204}\text{Pb}$: 37.18 ~ 37.37) [73], which are lower than the mantle mean values of 17.51, 15.43, and 37.63, respectively [74]. The diabase samples show relatively low Mg# (39–40), Ni (20.9–22.6 ppm), and Cr (20–23 ppm) contents, lower than primary mantle-derived magmas (Figure 7a). Such compositional variations indicate that their parental magmas might have been influenced by fractionation crystallization. The Aksu Neoproterozoic diabase dykes exhibit positive Eu anomalies ($\text{Eu}/\text{Eu}^* = 1.28\text{--}1.31$), indicating plagioclase fractionation (Figure 6). This conclusion is consistent with the petrological observation that the main components of diabase samples are clinopyroxene and plagioclase (Figure 3f). Moreover, these diabase dykes show high concentrations of fluid-mobile trace elements such as LILE and LREE, and distinctly negative Nb, Ta, Zr, Hf, and Ti anomalies, consistent with derivation from metasomatic SCLM sources. In addition, the similar elemental patterns of the Early Permian (287 Ma) diabase in Keping are interpreted to be derived from a metasomatic SCLM (Figure 6) [38]. This interpretation agrees with the radiogenic $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ from 0.7050 to 0.7074, $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of 0.511933–0.512346, and initial $\epsilon\text{Nd}_{(t)}$ values ranging from –6.4 to 1.5 of these diabase dykes [27,45], indicating that their parental magma may have been derived from subduction-related metasomatized SCLM [75,76]. Moreover, the diabase samples have relatively high Th/Yb ratios and low Nb/U ratios (Figure 10c,e,f), indicating that the SCLM was metasomatized by slab-derived fluids [76,77]. The high Th/Yb ratios and low Nb/U ratios are similar to mafic dyke samples from the SCLM of Jiaodong District, which experienced fluid-related metasomatism. Collectively, post-magmatic alteration, crustal contamination, and partial crystallization processes can be surmised to have had little effect on the composition of the studied diabase sample, the magma evolution of which involved subduction-related fluid metasomatism and limited contamination of the continental crust.

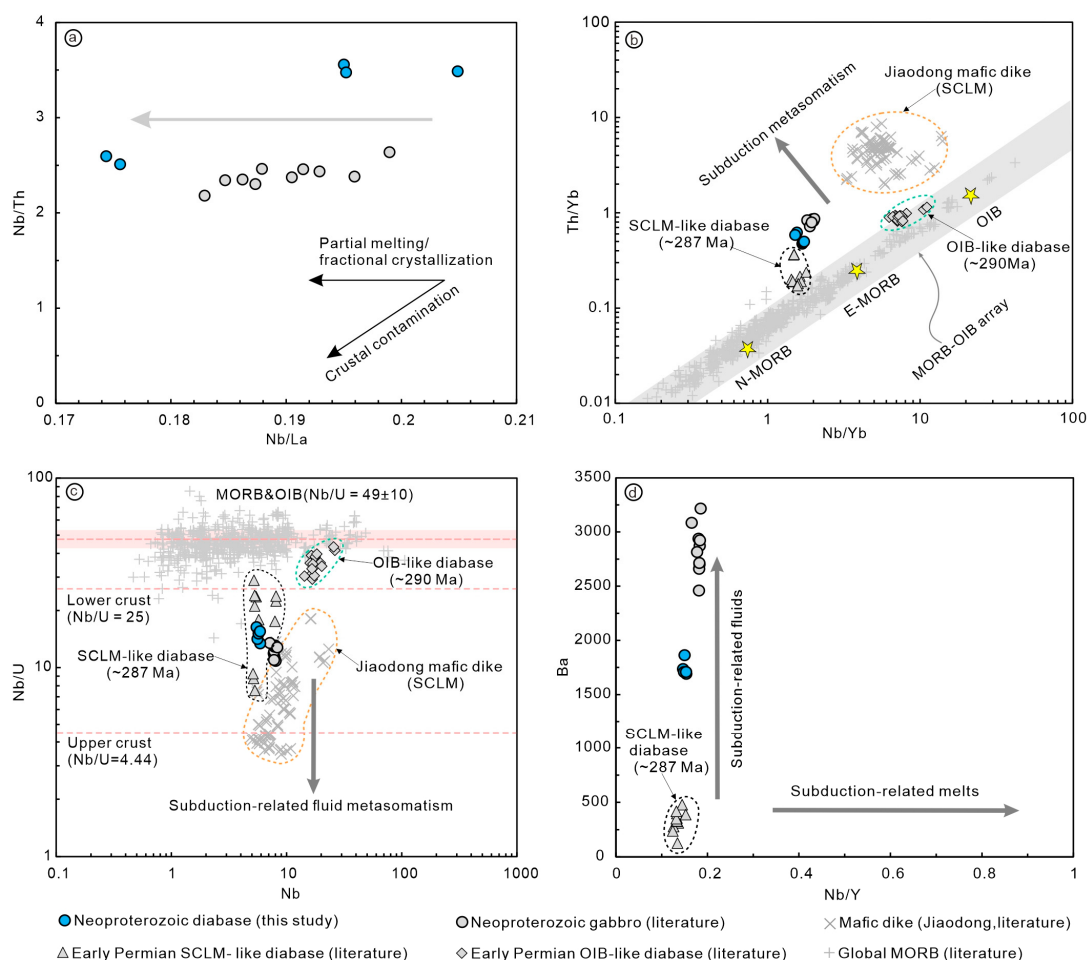


Figure 10. Variation diagrams to discern the petrogenesis for the Aksu Neoproterozoic diabase dykes. (a) Nb/La versus Nb/Th diagram, showing an uncontaminated trend. (b) Elevated Th/Yb at a given Nb/Yb indicates the involvement of subducted components (modified from [78]). (c) Nb/U versus Nb diagram outlines the subduction-related fluid metasomatism from the mantle component [79]. (d) Ba versus Nb/Y plot showing the modification by subduction slab fluids (from [80]). Data sources: Neoproterozoic gabbro [27,45], Early Permian diabase (OIBs and SCLM) [38], Jiaodong mafic dike [81], and Global MORB [82,83]. Literature data are compiled in Supplementary Table S1.

6.2. Mantle Source Evolution

The PGEs and Cu have distinctly different partition coefficients between sulfide and silicate melt, e.g., $D_{\text{PGE}} (10^5\text{--}10^6) > D_{\text{Cu}} (500\text{--}1500)$ [84]. Thus, sulfide saturation will increase Cu/Pd ratios so they are higher than in primitive mantle (~ 7000) [85]. The Cu/Pd ratios of the studied diabase dykes are significantly higher than those of the primitive mantle (Figure 8a,b), indicating that the diabase dyke rocks may have crystallized from S-saturated melts. In contrast, evolving magma under S-undersaturated melts may lead to elevated Pd/Ir ratios [86]. The Aksu Neoproterozoic diabase dykes have an extremely narrow range of Pd/Ir ratios (Figure 11b), which can be easily distinguished from the S-undersaturated basalt from the Deccan Traps [87]. This evidence further suggests that the parent magma of the diabase dykes is likely to have been S-saturated. Meanwhile, when the magma reaches sulfide saturation, the content of Cu in the magma will decrease, whereas the content of Zr will increase. In the Cu versus Zr diagram, the negative correlation between the Cu and Zr contents of these diabase dykes (Figure 11c) suggests the significant sulfide saturation of diabase dykes during magma evolution. In addition, these diabase dykes share a similar evolution trend to the sulfide-saturated Tarim basalt, Jiaodong lamprophyres, and MORBs (Figure 11c) [5,81,88]. This evolution trend may reflect sulfide

saturation of the mafic dykes during magma evolution. S-saturated magmas may lead to low Cu/Zr ratios of below 1 [89]. The Cu/Zr ratios of our diabase dykes are <0.5 (Figure 11d), analogous to those of sulfide-saturated Tarim basalt, Jiaodong lamprophyres, and MORBs [81,82,88]. In comparison, the Deccan Trap basalts show high Cu/Zr ratios and show positive correlation between Cu and Zr contents, meaning they are interpreted to be mainly crystallized from S-undersaturated melts (Figure 11c,d) [89]. These results further indicate that the parental melts of the diabase dykes could have been sulfide saturated.

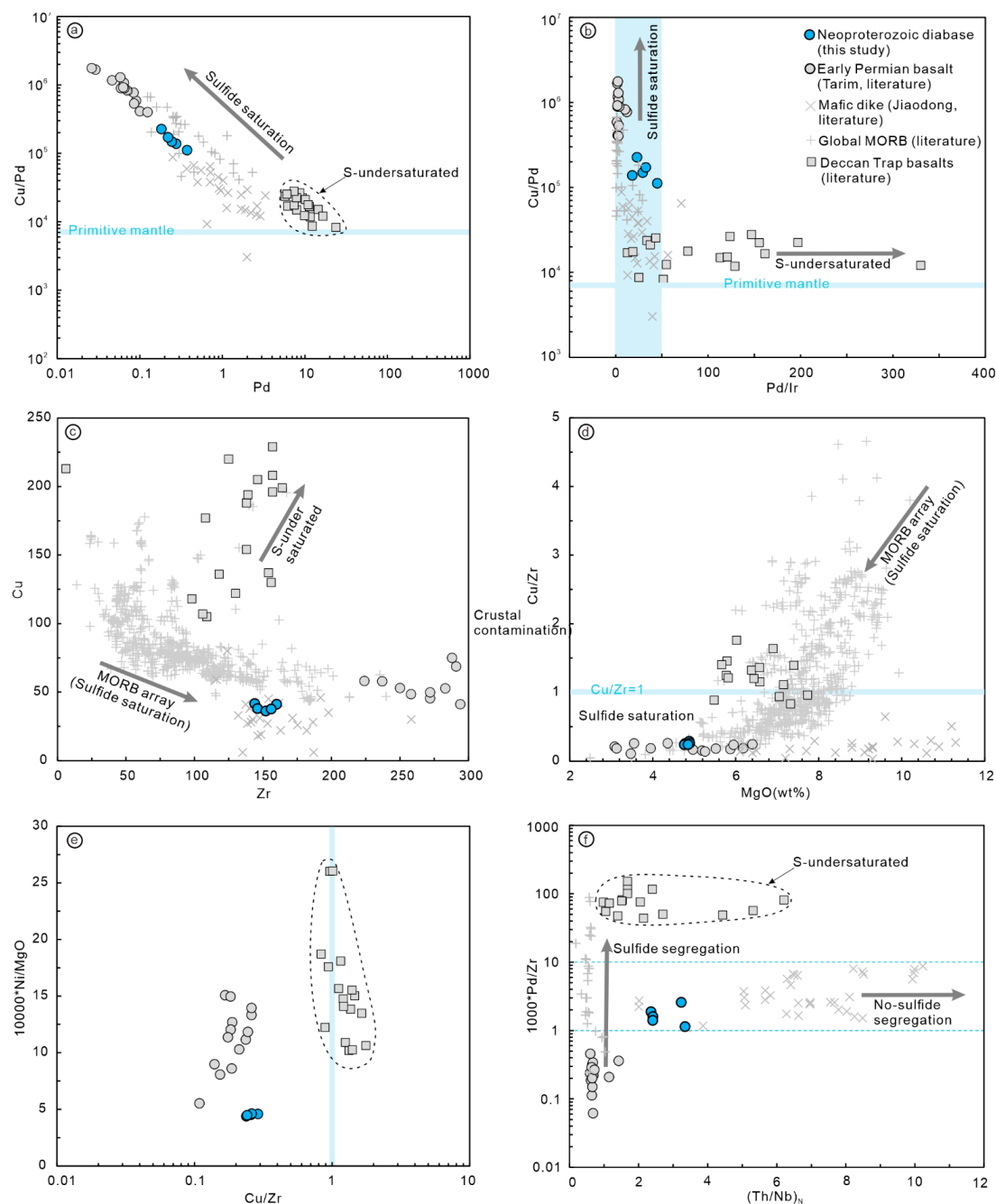


Figure 11. (a) Diagram showing variations in Cu/Pd ratios compared to Pd concentrations [85]. (b) Pd/Ir versus Cu/Pd diagram [88]. (c) Cu versus Zr diagram [89]. (d) Cu/Zr versus MgO diagram [89]. (e) Ni/MgO versus Cu/Zr diagram [87]. (f) Pd/Zr versus $(Th/Nb)_N$ diagram [87]. Data sources: Early Permian basalt [89], Jiaodong mafic dyke [5,81], Deccan Trap basalts [87], and Global MORB [82,83]. Literature data are compiled in Supplementary Table S2.

The S-saturation of magma can be caused by several different processes, such as crustal contamination, magma mixing, and low-degree partial melting. Theoretically, crustal contamination or magma mixing can cause the segregation of an immiscible sulfide melt [81]. The Ni/MgO and Cu/Zr ratios are also a good indicator to determine whether the parental magmas of mafic rocks met segregating magmatic sulfides during their ascent in the crust [87]. This is because Ni and Cu are partitioned into segregating magmatic sulfides, resulting in depletion of Ni and Cu in the parental magma [87]. However, the Ni/MgO ratios of the analyzed diabase dykes do not correlate with Cu/Zr ratios (Figure 8e), indicating that no segregation magmatic sulfides occurred during their melt evolution. This result is consistent with the absence of magmatic sulfides in these diabase dykes (Figure 3f). In addition, the variations in Pd/Zr and Cu/Pd ratios are sensitive to sulfide segregation because the partition coefficients of PGE in magmatic sulfides are two orders of magnitude larger than those of Cu and Ni [90]. The limited variation of Pd/Zr and Cu/Pd ratios in the studied diabase dykes (Figure 11f) further implies that the influence of crustal contamination and magma mixing on S-saturation and sulfide segregation could be excluded. This is consistent with the above results demonstrating that the diabase melt did not experience significant crustal contamination. It also conforms to the fact that the major element data of the studied diabase dykes did not abruptly increase or decrease, indicating that no magma mixing occurred. In addition, the SCLM-derived Jiaodong lamprophyres also show little change in Pd/Zr and Cu/Pd ratios (Figure 11f), which were explained initially as S-saturated, with no sulfide segregation caused by crustal contamination [81]. The variation in Pd/Zr and Th/Nb ratios of the Tarim basalt and East Pacific MORB (Figure 11f) were explained as S-saturated, with sulfide segregation accompanying magma mixing [83,88]. Therefore, the crustal contamination and magma mixing did not trigger sulfur saturation and sulfide segregation for the diabase magma in the crust. Low-degree partial melts are usually S-saturated as they leave the mantle, and they produce chalcophile-depleted melt [91]. The PGE patterns of the Aksu Neoproterozoic diabase dykes are markedly different from the Au-sulfide ores from the porphyry Cu-Au and orogenic Au deposit (Figure 7a) and the high-degree partial-melting felsic intrusions of the Tuwu Cu-Au deposit (Figure 7b). This result implies their derivation from low-degree melting of the SCLM source. Moreover, the Au, Pd, and Pt contents of these diabase dykes are lower than the SCLM-derived low-degree partial melting mafic dykes of Yilgarn Craton and Victoria gold province [58,60], which further indicates that the chalcophile elements are locked in the residue phase by low-degree partial melting of a metasomatized SCLM. Furthermore, the diabase dykes have low PGEs and are strongly depleted in Au contents (Figure 7a,b), indicating that their magmas were produced from S-saturated melts derived from low-degree partial melting of the SCLM. In this scenario, the formation of the Aksu diabase dykes will have left residual sulfide and chalcophile elements (PGEs, Au) in the SCLM source region, leading to elevated sulfide and Au contents in the SCLM, thus increasing the fertility of the SCLM beneath South Tianshan.

6.3. Contribution of Metasomatic SCLM on Regional Gold Metallogeny

Metasomatic processes can result in enrichment of Au of the SCLM, as evidenced by native Au nanoparticles (Patagonia [6]; Beiya [92]) and the high gold contents in mantle xenoliths elsewhere [82]. Neither metasomatized SCLM nor mantle-derived magmas have Au contents remarkably higher than that of global mantle peridotite (1.2 ppb) or normal mafic magmas such as MORBs (1–4 ppb) [82]. Although detailed inspection of the pyrite grains did not reveal native Au nanoparticles (Figure 3), the relatively high Au concentrations (up to 0.34 ppm) obtained by LA-ICP MS analyses indicate a discernible Au addition to their source. It should be noted that these pyrites contain significant amounts of Ag (up to 17.5 ppm, Supplementary Table S3). The Au/Ag ratios of pyrite from the analyzed diabase dykes are between 0.01 and 0.08, while the Au/Ag ratios of the Patagonian mantle sulfides vary from 0.02 to 0.96 (Figure 8) [6]. Thus, the Au/Ag ratios of the pyrite and the mantle sulfides are of a similar magnitude. Such similar metal ratios

indicate that the metasomatized SCLM may exert important control on the formation of the pyrite and gold contents in these diabase dykes. Furthermore, the Au/Ag ratios of the pyrite in the analyzed diabase dykes are similar to those of gold-bearing sulfides of the Awanda gold deposit (Figure 8; Au/Ag~0.01–4.59, our unpublished data). Similar Au/Ag ratios of gold-bearing sulfides are also observed in the lode gold deposit in the Jiaodong gold province (Figure 8; Supplementary Table S4). This similarity suggests that metasomatized SCLM may have contributed additional Au to the formation of the lode gold deposits in the region.

Moreover, pyrite of the Aksu diabase dykes is enriched in a host of trace elements such as Ti, Co, Ge, As, Ag, Pb, and low Au contents (0.01–0.34 ppm) while depleted in other metals such as V, Mn, Ga, Ti, Mo, and Bi (Figure 9). In addition, their distribution pattern is comparable to those from the gold-bearing sulfides of the Sawayaerdun gold deposit (Figure 9), indicating that the metasomatized SCLM may have contributed ore metals into the ore-forming fluid of the Sawayaerdun gold deposit.

7. Conclusions

The evolution of the SCLM-sourced Aksu Neoproterozoic diabase magma involved subduction-related fluid metasomatism with limited crustal contamination. Diabase magma might have been derived from low-degree partial melting under S-saturated condition, leaving PGEs and Au in the residual source region. Metasomatized SCLM may have contributed additional ore metals to the lode gold deposits in Chinese South Tianshan.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/min13030326/s1>, Table S1: Compilation of published whole-rock major (in wt.%) and trace element (in ppm) data for mafic dykes in Chinese South Tianshan; Table S2: Compilation of PGE, Cu, Ni, and S concentrations in ore and ore-related rocks from porphyry Cu–Au deposits and lode gold provinces worldwide; Table S3: In situ trace elements of pyrites from the Aksu Neoproterozoic diabase dykes and lode gold deposits in Chinese South Tianshan (data in ppm); Table S4: Compilation of in situ Au and Ag contents of pyrite from Patagonian mantle xenoliths and Jiaodong gold provinces (data in ppm).

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Data Availability Statement: Data are contained within the supplementary materials.

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References

1. McInnes, B.I.A.; McBride, J.S.; Evans, N.J.; Lambert, D.D.; Andrew, A.S. Osmium Isotope Constraints on Ore Metal Recycling in Subduction Zones. *Science* **1999**, *286*, 512–516. [[CrossRef](#)] [[PubMed](#)]
2. Griffin, W.L.; Begg, G.C.; O'Reilly, S.Y. Continental-root control on the genesis of magmatic ore deposits. *Nat. Geosci.* **2013**, *6*, 905–910. [[CrossRef](#)]
3. Wang, Q.; Zhao, H.; Groves, D.I.; Deng, J.; Zhang, Q.; Xue, S. The Jurassic Danba hypozonal orogenic gold deposit, western China: Indirect derivation from fertile mantle lithosphere metasomatized during Neoproterozoic subduction. *Miner. Depos.* **2020**, *55*, 309–324. [[CrossRef](#)]
4. Deng, J.; Wang, Q.; Santosh, M.; Liu, X.; Liang, Y.; Yang, L.; Zhao, R.; Yang, L. Remobilization of metasomatized mantle lithosphere: A new model for the Jiaodong gold province, eastern China. *Miner. Deposita* **2020**, *55*, 257–274. [[CrossRef](#)]

5. Wang, X.; Wang, Z.; Cheng, H.; Zong, K.; Wang, C.Y.; Ma, L.; Cai, Y.; Foley, S.; Hu, Z. Gold endowment of the metasomatized lithospheric mantle for giant gold deposits: Insights from lamprophyre dykes. *Geochim. Cosmochim. Acta* **2022**, *316*, 21–40. [\[CrossRef\]](#)
6. Tassara, S.; González-Jiménez, J.M.; Reich, M.; Schilling, M.E.; Morata, D.; Begg, G.; Saunders, E.; Griffin, W.L.O.; Reilly, S.Y.; Grégoire, M.; et al. Plume-subduction interaction forms large auriferous provinces. *Nat. Commun.* **2017**, *8*, 843. [\[CrossRef\]](#)
7. Zhao, H.; Wang, Q.; Kendrick, M.A.; Groves, D.I.; Fan, T.; Deng, J. Metasomatized mantle lithosphere and altered ocean crust as a fluid source for orogenic gold deposits. *Geochim. Cosmochim. Acta* **2022**, *334*, 316–337. [\[CrossRef\]](#)
8. Browning, P.; Groves, D.I.; Blockley, J.G.; Rosman, K.J.R. Lead isotope constraints on the age and source of gold mineralization in the Archean Yilgarn Block, Western Australia. *Econ. Geol.* **1987**, *82*, 971–986. [\[CrossRef\]](#)
9. Bierlein, F.P.; McNaughton, N.J. Pb isotope fingerprinting of mesothermal gold deposits from central Victoria, Australia: Implications for ore genesis. *Miner. Depos.* **1998**, *33*, 633–638. [\[CrossRef\]](#)
10. Large, R.R.; Maslennikov, V.V.; Robert, F.; Danyushevsky, L.V.; Chang, Z. Multistage Sedimentary and Metamorphic Origin of Pyrite and Gold in the Giant Sukhoi Log Deposit, Lena Gold Province, Russia. *Econ. Geol.* **2007**, *102*, 1233–1267. [\[CrossRef\]](#)
11. Chang, Z.; Large, R.R.; Maslennikov, V. Sulfur isotopes in sediment-hosted orogenic gold deposits: Evidence for an early timing and a seawater sulfur source. *Geology* **2008**, *36*, 971–974. [\[CrossRef\]](#)
12. Pitcairn, I.K.; Teagle, D.A.H.; Craw, D.; Olivo, G.R.; Kerrich, R.; Brewer, T.S. Sources of metals and fluids in orogenic gold deposits; insights from the Otago and Alpine Schists, New Zealand. *Econ. Geol. Bull. Soc. Econ. Geol.* **2006**, *101*, 1525–1546. [\[CrossRef\]](#)
13. Large, R.; Thomas, H.; Craw, D.; Henne, A.; Henderson, S. Diagenetic pyrite as a source for metals in orogenic gold deposits, Otago Schist, New Zealand. *N. Z. J. Geol. Geop.* **2012**, *55*, 137–149. [\[CrossRef\]](#)
14. Pitcairn, I.K.; Leventis, N.; Beaudoin, G.; Faure, S.; Guilmette, C.; Dubé, B. A metasedimentary source of gold in Archean orogenic gold deposits. *Geology* **2021**, *49*, 862–866. [\[CrossRef\]](#)
15. Yakubchuk, A.; Cole, A.; Seltsmann, R.; Shatov, V. Tectonic Setting, Characteristics, and Regional Exploration Criteria for Gold Mineralization in the Altaid Orogenic Collage: The Tien Shan Province as a Key Example. In *Integrated Methods for Discovery: Global Exploration in the Twenty-First Century*; Goldfarb, R.J., Nielsen, R.L., Eds.; Society of Economic Geologists: Littleton, CO, USA, 2002. [\[CrossRef\]](#)
16. Xue, C.; Zhao, X.; Mo, X.; Dong, L.; Gu, X.; Nurtaev, B.; Pak, N.; Zhang, Z.; Zu, B.; Zhang, G.; et al. Asian Gold Belt in western Tianshan and its dynamic setting, metallogenic control and exploration. *Earth Sci. Frontiers* **2014**, *21*, 128–155. (In Chinese with English Abstract)
17. Zhao, X.; Xue, C.; Zu, B.; Seltsmann, R.; Chi, G.; Dolgoplova, A.; Andersen, J.C.Ø.; Pak, N.; Ivleva, E. Geology and Genesis of the Unkurtash Intrusion-Related Gold Deposit, Tien Shan, Kyrgyzstan. *Econ. Geol.* **2022**, *117*, 1073–1103. [\[CrossRef\]](#)
18. Seltsmann, R.; Goldfarb, R.J.; Zu, B.; Creaser, R.A.; Dolgoplova, A.; Shatov, V.V. Chapter 24: Muruntau, Uzbekistan: The World's Largest Epigenetic Gold Deposit. In *Geology of the World's Major Gold Deposits and Provinces*; Sillitoe, R.H., Goldfarb, R.J., Robert, F., Simmons, S.F., Eds.; Society of Economic Geologists: Littleton, CO, USA, 2020; Volume 23. [\[CrossRef\]](#)
19. Graupner, T.; Niedermann, S.; Kempe, U.; Klemm, R.; Bechtel, A. Origin of ore fluids in the Muruntau gold system: Constraints from noble gas, carbon isotope and halogen data. *Geochim. Cosmochim. Acta* **2006**, *70*, 5356–5370. [\[CrossRef\]](#)
20. Morelli, R.; Creaser, R.A.; Seltsmann, R.; Stuart, F.M.; Selby, D.; Graupner, T. Age and source constraints for the giant Muruntau gold deposit, Uzbekistan, from coupled Re-Os-He isotopes in arsenopyrite. *Geology* **2007**, *35*, 795–798. [\[CrossRef\]](#)
21. Mao, J.; Konopelko, D.; Seltsmann, R.; Lehmann, B.; Chen, W.; Wang, Y.; Eklund, O.; Usabaliev, T. Postcollisional Age of the Kumtor Gold Deposit and Timing of Hercynian Events in the Tien Shan, Kyrgyzstan. *Econ. Geol.* **2004**, *99*, 1771–1780. [\[CrossRef\]](#)
22. Wall, V.J.; Graupner, T.; Yantsen, V.; Seltsmann, R.; Hall, G.C.; Muhling, J. Muruntau, Uzbekistan: A giant thermal aureole gold (TAG) system. *SEG* **2004**, *1*, 199–203.
23. Goldfarb, R.J.; Groves, D.I. Orogenic gold: Common or evolving fluid and metal sources through time. *Lithos* **2015**, *233*, 2–26. [\[CrossRef\]](#)
24. Chen, H.; Chen, Y.; Baker, M. Isotopic geochemistry of the Sawayaerdun orogenic-type gold deposit, Tianshan, northwest China: Implications for ore genesis and mineral exploration. *Chem. Geol.* **2012**, *310–311*, 1–11. [\[CrossRef\]](#)
25. Zhang, C.; Li, Z.; Li, X.; Ye, H. Neoproterozoic mafic dyke swarms at the northern margin of the Tarim Block, NW China: Age, geochemistry, petrogenesis and tectonic implications. *J. Asian Earth Sci.* **2009**, *35*, 167–179. [\[CrossRef\]](#)
26. Konopelko, D.; Klemm, R.; Petrov, S.V.; Apayarov, F.; Nazaraliev, B.; Vokueva, O.; Scherstén, A.; Sergeev, S. Precambrian gold mineralization at Djamgyr in the Kyrgyz Tien Shan: Tectonic and metallogenic implications. *Ore Geol. Rev.* **2017**, *86*, 537–547. [\[CrossRef\]](#)
27. Ding, Q.; Wu, C.; Santosh, M.; Fu, Y.; Dong, L.; Qu, X.; Gu, L. H-O, S and Pb isotope geochemistry of the Awanda gold deposit in southern Tianshan, Central Asian orogenic belt: Implications for fluid regime and metallogeny. *Ore Geol. Rev.* **2014**, *62*, 40–53. [\[CrossRef\]](#)
28. Jun, G.; Maosong, L.; Xuchang, X.; Yaoqing, T.; Guoqi, H. Paleozoic tectonic evolution of the Tianshan Orogen, northwestern China. *Tectonophysics* **1998**, *287*, 213–231. [\[CrossRef\]](#)
29. Xiao, W.; Windley, B.F.; Allen, M.B.; Han, C. Paleozoic multiple accretionary and collisional tectonics of the Chinese Tianshan orogenic collage. *Gondwana Res.* **2013**, *23*, 1316–1341. [\[CrossRef\]](#)
30. Huang, H.; Zhang, Z.; Santosh, M.; Zhang, D.; Wang, T. Petrogenesis of the Early Permian volcanic rocks in the Chinese South Tianshan: Implications for crustal growth in the Central Asian Orogenic Belt. *Lithos* **2015**, *228–229*, 23–42. [\[CrossRef\]](#)

31. Bgmrxuar. *Regional Geology of Xinjiang Uygur Autonomous Region*; Geological Publishing House: Beijing, China, 1993; p. 409. (In Chinese)
32. Yang, F.; Mao, J.; Wang, Y.; Bierlein, F.P. Geology and geochemistry of the Bulong quartz–barite vein-type gold deposit in the Xinjiang Uygur Autonomous Region, China. *Ore Geol. Rev.* **2006**, *29*, 52–76. [\[CrossRef\]](#)
33. Xue, C.; Zhao, X.; Zhao, W.; Zhao, Y.; Zhang, G.; Nurtaev, B.; Pak, N.; Mo, X. 2020, Deformed zone hosted gold deposits in the China-Kazakhstan-Kyrgyzstan-Uzbekistan Tianshan: Metallogenic environment, controlling parameters, and prospecting criteria. *Earth Sci. Front.* (In Chinese with English Abstract). **2020**, *27*, 294–319.
34. Liu, D.; Guo, Z.; Jolivet, M.; Cheng, F.; Song, Y.; Zhang, Z. Petrology and geochemistry of Early Permian volcanic rocks in South Tian Shan, NW China: Implications for the tectonic evolution and Phanerozoic continental growth. *Int. J. Earth Sci.* **2014**, *103*, 737–756. [\[CrossRef\]](#)
35. Han, Y.; Zhao, G. Final amalgamation of the Tianshan and Junggar orogenic collage in the southwestern Central Asian Orogenic Belt: Constraints on the closure of the Paleo-Asian Ocean. *Earth-Sci. Rev.* **2018**, *186*, 129–152. [\[CrossRef\]](#)
36. Konopelko, D.; Biske, G.; Seltnmann, R.; Eklund, O.; Belyatsky, B. Hercynian post-collisional A-type granites of the Kokshaal Range, Southern Tien Shan, Kyrgyzstan. *Lithos* **2007**, *97*, 140–160. [\[CrossRef\]](#)
37. Zhang, Y.; Liu, J.; Guo, Z. Permian basaltic rocks in the Tarim basin, NW China: Implications for plume–lithosphere interaction. *Gondwana Res.* **2010**, *18*, 596–610. [\[CrossRef\]](#)
38. Cheng, X.; Wu, H.; Sun, D.; Huang, W.; Chen, H.; Lin, X.; Zhu, K.; Zhang, F. The Permian mafic intrusive events in the northwestern margin of the Tarim Basin and their tectonic significance. *Acta Petrologica Sinica*. **2022**, *38*, 743–764. (In Chinese with English abstract)
39. Liou, J.G.; Graham, S.A.; Maruyama, S.; Zhang, R.Y. Characteristics and Tectonic Significance of the Late Proterozoic Aksu Blueschists and Diabasic Dykes, Northwest Xinjiang, China. *Int. Geol. Rev.* **1996**, *38*, 228–244. [\[CrossRef\]](#)
40. Xia, B.; Zhang, L.; Du, Z.; Xu, B. Petrology and age of Precambrian Aksu blueschist, NW China. *Precambrian Res.* **2019**, *326*, 295–311. [\[CrossRef\]](#)
41. Lu, Y.; Zhu, W.; Jourdan, F.; Ge, R.; Cui, X.; Wen, B. $^{40}\text{Ar}/^{39}\text{Ar}$ ages and geological significance of Neoproterozoic–Cambrian mafic rocks in the Aksu–Wushi area, NW Tarim Craton. *Geol. J.* **2019**, *54*, 3803–3820. [\[CrossRef\]](#)
42. Yong, W.; Zhang, L.; Hall, C.M.; Mukasa, S.B.; Essene, E.J. The $^{40}\text{Ar}/^{39}\text{Ar}$ and Rb–Sr chronology of the Precambrian Aksu blueschists in western China. *J. Asian Earth Sci.* **2013**, *63*, 197–205. [\[CrossRef\]](#)
43. Zhu, W.; Zheng, B.; Shu, L.; Ma, D.; Wu, H.; Li, Y.; Huang, W.; Yu, J. Neoproterozoic tectonic evolution of the Precambrian Aksu blueschist terrane, northwestern Tarim, China: Insights from LA-ICP-MS zircon U–Pb ages and geochemical data. *Precambrian Res.* **2011**, *185*, 215–230. [\[CrossRef\]](#)
44. Zheng, B.; Zhu, W.; Jahn, B.; Shu, L.; Zhang, Z.; Su, J. Subducted Precambrian oceanic crust: Geochemical and Sr–Nd isotopic evidence from metabasalts of the Aksu blueschist, NW China. *J. Geol. Soc. London* **2010**, *167*, 1161–1170. [\[CrossRef\]](#)
45. Cai, Z.; He, B.; Meert, J.G.; Ma, X.; Jiao, C.; Liu, R.; Chen, X.; Yun, X. Neoproterozoic tectonic transition from subduction-related convergence to continental extension of the Tarim Block, NW China. *Precambrian Res.* **2021**, *362*, 106278. [\[CrossRef\]](#)
46. Sun, S.S.; McDonough, W.F. Chemical and Isotopic Systematics of Oceanic Basalts: Implications for Mantle Composition and Processes. In *Geological Society; Special Publications*: London, UK, 1989; pp. 313–345.
47. Nadeau, O.; Williams-Jones, A.E.; Stix, J. Sulphide magma as a source of metals in arc-related magmatic hydrothermal ore fluids. *Nat. Geosci.* **2010**, *3*, 501–505. [\[CrossRef\]](#)
48. Liang, Q.; Grégoire, D.C. Determination of Trace Elements in Twenty Six Chinese Geochemistry Reference Materials by Inductively Coupled Plasma–Mass Spectrometry. *Geostand. Newsl.* **2000**, *24*, 51–63. [\[CrossRef\]](#)
49. Qi, L.; Gao, J.; Huang, X.; Hu, J.; Zhou, M.; Zhong, H. An improved digestion technique for determination of platinum group elements in geological samples. *J. Anal. Atom. Spectrom.* **2011**, *26*, 1900–1904. [\[CrossRef\]](#)
50. Danyushevsky, L.; Robinson, P.; Gilbert, S.; Norman, M.; Large, R.; McGoldrick, P.; Shelley, M. Routine quantitative multi-element analysis of sulphide minerals by laser ablation ICP-MS: Standard development and consideration of matrix effects. *Geochem. Explor. Environ. Anal.* **2011**, *11*, 51–60. [\[CrossRef\]](#)
51. Wilson, S.A.; Ridley, W.I.; Koenig, A.E. Development of sulfide calibration standards for the laser ablation inductively-coupled plasma mass spectrometry technique. *J. Anal. Atom. Spectrom.* **2002**, *17*, 406–409. [\[CrossRef\]](#)
52. Liu, Y.; Hu, Z.; Gao, S.; Günther, D.; Xu, J.; Gao, C.; Chen, H. In situ analysis of major and trace elements of anhydrous minerals by LA-ICP-MS without applying an internal standard. *Chem. Geol.* **2008**, *257*, 34–43. [\[CrossRef\]](#)
53. Longerich, H.P.; Jackson, S.E.; Günther, D. Laser ablation inductively coupled plasma mass spectrometric transient signal data acquisition and analyte concentration calculation. *J. Anal. At. Spectrom.* **1996**, *11*, 899–904. [\[CrossRef\]](#)
54. Lebas, M.J.; Lemaitre, R.W.; Streckeisen, A.; Zanettin, B. A chemical classification of volcanic rocks based on the total alkali–silica diagram. *J. Petrol.* **1986**, *27*, 745–750.
55. Winchester, J.A.; Floyd, P.A. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chem. Geol.* **1977**, *20*, 325–343. [\[CrossRef\]](#)
56. Miyashiro, A. Classification, Characteristics, and Origin of Ophiolites. *J. Geol.* **1975**, *83*, 249–281. [\[CrossRef\]](#)
57. Peccerillo, A.; Taylor, S.R. Geochemistry of eocene calc-alkaline volcanic rocks from the Kastamonu area, Northern Turkey. *Contrib. Mineral. Petr.* **1976**, *58*, 63–81. [\[CrossRef\]](#)

58. Jowitt, S.M.; Keays, R.R.; Jackson, P.G.; Hoggart, C.R.; Green, A.H. Mineralogical and Geochemical Controls on the Formation of the Woods Point Dike Swarm, Victoria, Australia: Evidence from the Morning Star Dike and Implications for Sourcing of Au Within Orogenic Gold Systems. *Econ. Geol.* **2012**, *107*, 251–273. [\[CrossRef\]](#)
59. Gan, T.; Huang, Z. Platinum-group element and Re-Os geochemistry of lamprophyres in the Zhenyuan gold deposit, Yunnan Province, China: Implications for petrogenesis and mantle evolution. *Lithos* **2017**, *282–283*, 228–239. [\[CrossRef\]](#)
60. Choi, E.; Fiorentini, M.L.; Hughes, H.S.R.; Giuliani, A. Platinum-group element and Au geochemistry of Late Archean to Proterozoic calc-alkaline and alkaline magmas in the Yilgarn Craton, Western Australia. *Lithos* **2020**, *374–375*, 105716. [\[CrossRef\]](#)
61. Gao, J.; Zhou, M.; Qi, L.; Chen, W.T.; Huang, X. Chalcophile elemental compositions and origin of the Tuwu porphyry Cu deposit, NW China. *Ore Geol. Rev.* **2015**, *66*, 403–421. [\[CrossRef\]](#)
62. Thompson, J.; Lang, J.; Stanley, C. *Platinum Group Elements in Alkaline Porphyry Deposits, British Columbia*; Exploration and Mining in British Columbia, Mines Branch: Vancouver, BC, Canada, 2001.
63. Deng, J.; Wang, Z.; Guo, L.; Li, R.; Groves, D.I.; Danyushevsky, L.V.; Zhang, C.; Zheng, X.; Zhao, H. Relationships Between Gold and Pyrite at the Xincheng Gold Deposit, Jiaodong Peninsula, China: Implications for Gold Source and Deposition in a Brittle Epizonal Environment. *Econ. Geol.* **2016**, *111*, 105–126. [\[CrossRef\]](#)
64. Li, X.; Fan, H.; Zhu, R.; Steele-Macinnis, M.; Yang, K.; Liu, C. Texture, geochemistry, and geochronology of titanite and pyrite: Fingerprint of magmatic-hydrothermal fertile fluids in the Jiaodong Au province. *Am. Mineral.* **2022**, *107*, 206–220. [\[CrossRef\]](#)
65. Li, X.; Wang, Y.; Li, Y.; Fu, L.; Zhang, M.; Wu, X.; Zhao, Y.; Huang, X.; Xu, C.; Kong, F. Micro-geochemical characteristic of pyrites in the Heilangou gold deposit of penglai area and its implications for ore-forming fluid. *Geol. Bull. China* **2022**, *41*, 1023–1038. [\[CrossRef\]](#)
66. Wu, J.; Zeng, Q.; Santosh, M.; Fan, H.; Bai, R.; Li, X.; Zhang, Z.; Zhang, Y.; Huang, L. Deep ore-forming fluid characteristics of the Jiaodong gold province: Evidence from the Qianchen gold deposit in the Jiaojia gold belt. *Ore Geol. Rev.* **2022**, *145*, 104911. [\[CrossRef\]](#)
67. Li, Q.; Song, H.; Chi, G.; Zhang, G.; Xu, Z. Genesis of visible gold in pyrite in the Zhaoxian gold deposit, Jiaodong gold province, China: Constraints from EBSD micro-structural and LA-ICP-MS elemental analyses. *Ore Geol. Rev.* **2021**, *139*, 104591. [\[CrossRef\]](#)
68. Lan, T.; Fan, Y.; Lu, J.; Hao, L.; Zhao, X.; Sun, X.; Guo, J.; Hou, Y. Origin of the Dayingezhuang gold deposit in the Jiaodong district, eastern China: Insights from trace element character of pyrite and C-O-S isotope compositions. *Geochem. Explor.* **2022**, *236*, 106986. [\[CrossRef\]](#)
69. Liu, Z.; Mao, X.; Jedermann, A.; Bayless, R.C.; Deng, H.; Chen, J.; Xiao, K. Evolution of Pyrite Compositions at the Sizhuang Gold Deposit, Jiaodong Peninsula, Eastern China: Implications for the Genesis of Jiaodong-Type Orogenic Gold Mineralization. *Minerals* **2021**, *11*(4), 344. [\[CrossRef\]](#)
70. Lin, Z.; Zhao, X.; Xiong, L. In-situ trace element analysis characteristics of pyrite in Sanshandao Gold Deposit in Jiaodong Peninsula: Implications for ore genesis. *Adv. Earth Sci.* **2019**, *34*, 399–413. [\[CrossRef\]](#)
71. Zhang, G.; Xue, C.; Liu, J.; Zhao, X.; Feng, C.; Meng, B. The ore-forming process of the Sawayaerdun gold deposit, western Tianshan, Xinjiang: Constraints from the generation relationship and EMPA, LA-ICP-MS and FESEM analysis of the Pyrite and Arsenopyrite. *Geol. China* **2022**, *49*, 16–35, (In Chinese with English Abstract).
72. Rudnick, R.L.; Fountain, D.M. Nature and composition of the continental crust: A lower crustal perspective. *Rev. Geophys.* **1995**, *33*, 267–309. [\[CrossRef\]](#)
73. Ma, G.; Zhao, X.; Xue, C.; Seltnann, R.; Dolgoplova, A.; Wang, R. Deciphering sources of lode gold deposits in the South Tianshan, NW China: Insights from Pb isotope systematics. *Miner. Deposita* **2023**, *under review*.
74. Zartman, R.E.; Haines, S.M. The plumbotectonic model for Pb isotopic systematics among major terrestrial reservoirs—A case for bi-directional transport. *Geochim. Cosmochim. Acta* **1988**, *52*, 1327–1339. [\[CrossRef\]](#)
75. Abdelfadil, K.M.; Romer, R.L.; Seifert, T.; Lobst, R. Calc-alkaline lamprophyres from Lusatia (Germany)—Evidence for a repeatedly enriched mantle source. *Chem. Geol.* **2013**, *353*, 230–245. [\[CrossRef\]](#)
76. Abdelfadil, K.M.; Saleh, G.M.; Putiš, M.; Sami, M. Mantle source characteristics of the late Neoproterozoic post-collisional gabbroic intrusion of Wadi Abu Hadieda, north Arabian-Nubian Shield, Egypt. *J. Afr. Earth Sci.* **2022**, *194*, 104607. [\[CrossRef\]](#)
77. Abdelfadil, K.M.; Romer, R.L.; Glodny, J. Mantle wedge metasomatism revealed by Li isotopes in orogenic lamprophyres. *Lithos* **2014**, *196–197*, 14–26. [\[CrossRef\]](#)
78. Pearce, J.A. Immobile Element Fingerprinting of Ophiolites. *Elements* **2014**, *10*, 101–108. [\[CrossRef\]](#)
79. Ayers, J. Trace element modeling of aqueous fluid–peridotite interaction in the mantle wedge of subduction zones. *Contrib. Mineral. Petr.* **1998**, *132*, 390–404. [\[CrossRef\]](#)
80. Kepezhinskis, P.M.F.D. Trace element and Sr-Nd-Pb isotopic constraints on a three-component model of Kamchatka Arc petrogenesis. *Geochim. Et Cosmochim. Acta J. Geochem. Soc. Meteorit. Soc.* **1997**, *16*, 577–600. [\[CrossRef\]](#)
81. Deng, J.; Liu, X.; Wang, Q.; Dilek, Y.; Liang, Y. Isotopic characterization and petrogenetic modeling of Early Cretaceous mafic diking—Lithospheric extension in the North China craton, eastern Asia. *GSA Bull.* **2017**, *129*, 1379–1407. [\[CrossRef\]](#)
82. Jenner, F.E.; O'Neill, H.S.C. Analysis of 60 elements in 616 ocean floor basaltic glasses. *Geochem. Geophys. Geosy.* **2012**, *13*, 2. [\[CrossRef\]](#)
83. Hao, H.; Campbell, I.H.; Arculus, R.J.; Perfit, M.R. Using precious metal probes to quantify mid-ocean ridge magmatic processes. *Earth Planet Sci. Lett.* **2021**, *553*, 116603. [\[CrossRef\]](#)

84. Mungall, J.E.; Brenan, J.M. Partitioning of platinum-group elements and Au between sulfide liquid and basalt and the origins of mantle-crust fractionation of the chalcophile elements. *Geochim. Cosmochim. Acta* **2014**, *125*, 265–289. [[CrossRef](#)]
85. Barnes, S.; Couture, J.F.; Sawyer, E.W.; Bouchaib, C. Nickel-copper occurrences in the Belleterre-Angliers Belt of the Pontiac Subprovince and the use of Cu-Pd ratios in interpreting platinum-group element distributions. *Econ. Geol.* **1993**, *88*, 1402–1418. [[CrossRef](#)]
86. Momme, P.; Tegner, C.; Brooks, K.C.; Keays, R.R. The behaviour of platinum-group elements in basalts from the East Greenland rifted margin. *Contrib. Mineral. Petr.* **2002**, *143*, 133–153. [[CrossRef](#)]
87. Keays, R.R.; Lightfoot, P.C. Crustal sulfur is required to form magmatic Ni–Cu sulfide deposits: Evidence from chalcophile element signatures of Siberian and Deccan Trap basalts. *Miner. Depos.* **2010**, *45*, 241–257. [[CrossRef](#)]
88. Li, Y.; Li, Z.; Sun, Y.; Santosh, M.; Langmuir, C.H.; Chen, H.; Yang, S.; Chen, Z.; Yu, X. Platinum-group elements and geochemical characteristics of the Permian continental flood basalts in the Tarim Basin, northwest China: Implications for the evolution of the Tarim Large Igneous Province. *Chem. Geol.* **2012**, *328*, 278–289. [[CrossRef](#)]
89. Lightfoot, P.C.; Keays, R.R. Siderophile and Chalcophile Metal Variations in Flood Basalts from the Siberian Trap, Noril'sk Region: Implications for the Origin of the Ni–Cu–PGE Sulfide Ores. *Econ. Geol.* **2005**, *100*, 439–462. [[CrossRef](#)]
90. Peach, C.L.; Mathez, E.A.; Keays, R.R. Sulfide melt-silicate melt distribution coefficients for noble metals and other chalcophile elements as deduced from MORB: Implications for partial melting. *Geochim. Cosmochim. Acta* **1990**, *54*, 3379–3389. [[CrossRef](#)]
91. Jugo, P.J.; Luth, R.W.; Richards, J.P. An experimental study of the sulfur content in basaltic melts saturated with immiscible sulfide or sulfate liquids at 1300 °C and 1 × 0 GPa. *J. Petrol.* **2005**, *46*, 783–798. [[CrossRef](#)]
92. Hou, Z.; Zhou, Y.; Wang, R.; Zheng, Y.; He, W.; Zhao, M.; Evans, N.J.; Weinberg, R.F. Recycling of metal-fertilized lower continental crust: Origin of non-arc Au-rich porphyry deposits at cratonic edges. *Geology* **2017**, *45*, 563–566. [[CrossRef](#)]

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