



The genesis of the ores and intrusions at the Yuhai Cu–Mo deposit in eastern Tianshan, NW China: Constraints from geology, geochronology, geochemistry, and Hf isotope systematics



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ABSTRACT

The Yuhai porphyry Cu–Mo deposit is located in the eastern Tianshan orogenic belt of the southern Central Asian Orogen Belt, being an economically important porphyry Cu deposit in NW China. The deposit comprises sixteen buried orebodies that are predominantly associated with dioritic and granodioritic intrusions and are structurally controlled by roughly NE-trending faults. LA-ICP-MS zircon U–Pb dating yielded crystallization ages of 441.6 ± 2.5 Ma (MSWD = 0.03, $n = 24$) for diorite and 430.4 ± 2.9 Ma (MSWD = 0.04, $n = 19$) and 430.3 ± 2.6 Ma (MSWD = 0.09, $n = 24$) for granodiorite. In situ zircon Hf isotope data on a diorite sample show $\varepsilon_{\text{Hf}}(t)$ values from +8.7 to +18.6, and two granodiorite samples exhibit similar $\varepsilon_{\text{Hf}}(t)$ values from +12.6 to +19.6 and +12.6 to +18.9, respectively. The dioritic and granodioritic intrusions belong to a low-K tholeiite series and are relatively enriched in large ion lithophile elements (K, Ba, Pb, and Sr) and are depleted in high field strength elements (Th, Nb, Ta, and Ti). Moreover, these intrusions have high SiO_2 , Al_2O_3 and MgO contents, low Na_2O , P_2O_5 and TiO_2 contents, low Nb/Ta ratios, and slightly positive Eu anomalies. Re–Os dating of molybdenite intergrowth with chalcopyrite yielded a well-constrained ^{187}Re – ^{187}Os isochron age of 351.7 ± 2.9 Ma (MSWD = 1.5) with a weighted average age of 355.7 ± 2.4 Ma (MSWD = 0.69) Ma, indicating that the Yuhai Cu–Mo deposit is younger than the intrusion of the diorite and granodiorite. Combined with the regional geological history and above-mentioned data, we suggest that the Yuhai intrusions were most likely derived from the partial melting of mantle components that were previously metasomatized by slab melts formed by the northward subduction of the ancient Tianshan ocean plate beneath the Dananhu–Tousuquan island arc during the Silurian to Carboniferous. Under the subduction-related tectonic setting, the metasomatized mantle magma was emplaced into the shallow crust and induced the formation of the Early Carboniferous Yuhai Cu–Mo deposit, and the hydrothermal fluids of enriched sulfides probably played an important role in the Cu–Mo mineralization.

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1. Introduction

The Central Asian Orogenic Belt (CAOB) is one of the largest Phanerozoic accretionary orogens in the world (Windley et al., 2007; Xiao and Santosh, 2014; Zhao et al., 2015). The formation of the CAOB is considered to be a result of the Paleo-Asian Ocean closure, involving lateral accretion of island arcs, ophiolites, oceanic islands, seamounts, accretionary wedges, oceanic plateaus and microcontinents (Sengör et al., 1993; Cawood et al., 2009; Xiao et al., 2015a). The west–east trending eastern Tianshan orogenic belt, which is located along the southern margin of the CAOB (Fig. 1A, B; Chen et al., 2012b; Huang et al., 2013), is one of the most important tectonic–magmatic–metallogenic belt in China (Xiao et al., 2004, 2010; Deng et al., 2014, 2015a; Wang et al.,

2014, 2015a) and experienced a complex tectonic evolution including subduction, accretion and the subsequent collision between the Siberian Craton to the north and the Tarim Craton to the south (Mao et al., 2014; Pirajno, 2010, 2013; Tang et al., 2015; Xue et al., 2014, 2015). Thus eastern Tianshan represents a key area for understanding the tectonic evolution of the CAOB. According to previous studies, widespread magmatism has taken place in the eastern Tianshan orogenic belt, which is characterized by voluminous Paleozoic granitoid intrusions (Zhou et al., 2010; Pirajno et al., 2011; Wang et al., 2015b, c). The formation of numerous metal deposits were closely associated with the Paleozoic magmatic hydrothermal activity in eastern Tianshan, including the Tuwu–Yandong Cu deposit (Shen et al., 2014; Wang et al., 2015b, c), Chihu Cu deposit (Wu et al., 2006b; Zhang et al., 2015b), Sanchakou Cu deposit (Qin et al., 2009), Hongshi Au deposit (Pirajno et al., 1997, 2011; Wang et al., 2016a), Yamansu Fe–Cu deposit (Hou et al., 2014) and Weiquan Ag–Cu deposit (Han et al., 2006).

The Yuhai Cu deposit located within the northeastern part of the eastern Tianshan (Fig. 1C), Xinjiang, China, is one of the economically

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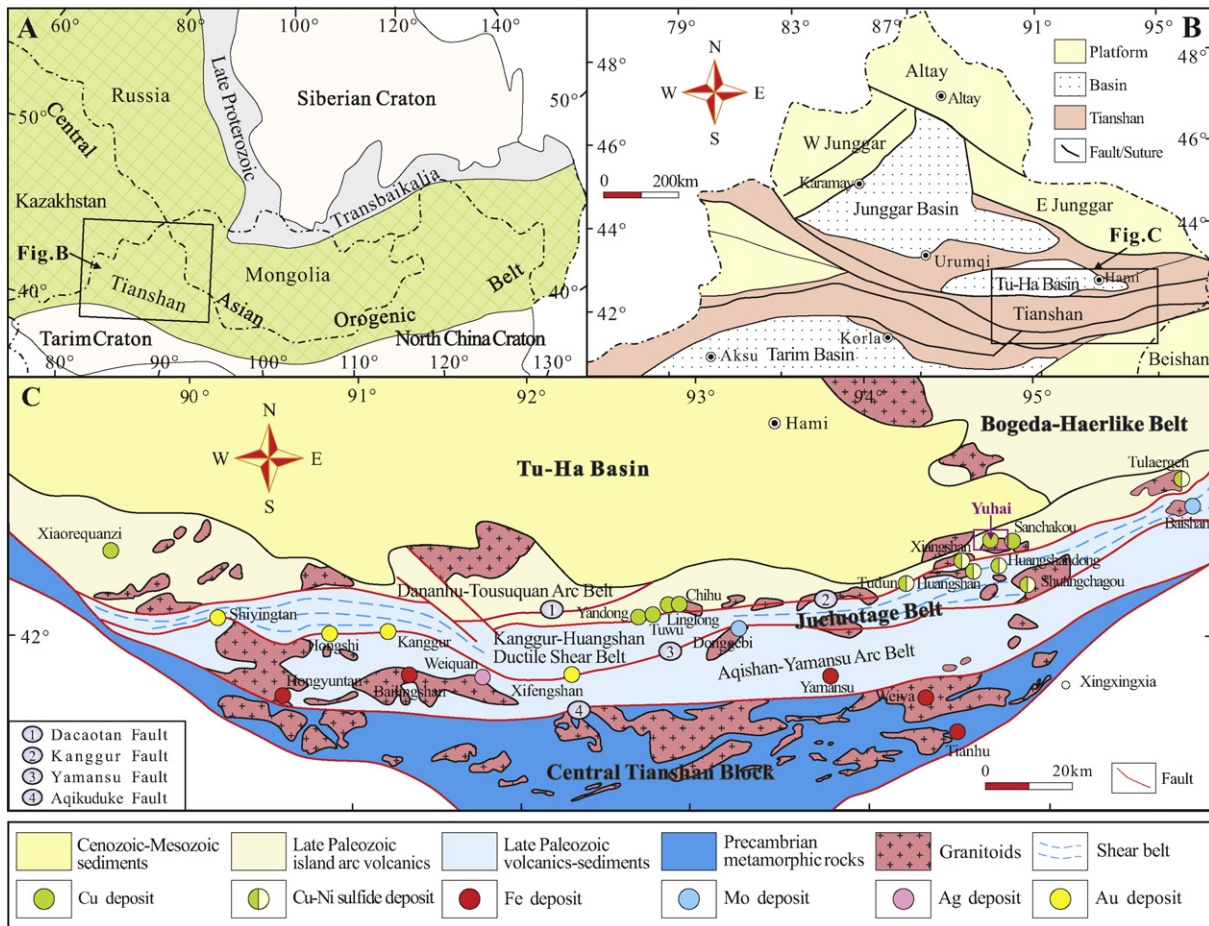


Fig. 1. (A) Location of the study area in the Central Asian Orogenic Belt. (B) Sketch map showing the geological units of the Tianshan Belt. (C) Simplified geological map of the eastern Tianshan Belt.

Panel A is modified from Jahn et al. (2000). Panel B is modified from Chen et al. (2012b). Panel C is modified from Huang et al. (2013).

most important porphyry Cu area in the province. It was first identified in 2011 during an assessment of geochemical anomalies by the No. 704 Geological Team of the Xinjiang Nonferrous Geology Exploration Bureau, and the detailed geological mapping and lab-based research undertaken during this period suggested that this was a porphyry deposit that was spatially and potentially genetically associated with the diorite and granodiorite. To date, however, only minimal basic geological research has been undertaken in this area (Zang, 2014; Wei, 2015), which means that the ore-forming processes, tectonic settings and ages of the ore-forming related intrusions are all unclear. In this study, we present new LA-ICP-MS zircon U–Pb dating, whole-rock geochemical data, in situ zircon Hf isotopic compositions and molybdenite Re–Os ages to constrain the magma source of intrusions and the timing of mineralization in the Yuhai deposit and to further explore their genetic relationships and tectonic settings. This study provides new information on the prospectivity of this area and the wider eastern Tianshan orogenic belt for porphyry Cu mineralization.

2. Geological setting

2.1. Regional geology

The eastern Tianshan orogenic belt is a typical Paleozoic island arc system characterized by a complex tectonic history and diverse styles of mineral systems (Zhai et al., 1999, 2011; Charvet et al., 2007; Xiao et al., 2010, 2013; Chen et al., 2012a; Pirajno, 2013). It can be divided into three major tectonic zones: the Bogeda–Haerlike belt, the Jueluotage belt and the Central Tianshan block from the north to the south (Fig. 1C).

These tectonic zones have different rock associations and host distinct mineralizations (Pirajno et al., 2011; Qin et al., 2011; Chen et al., 2012b). The Bogeda–Haerlike belt comprises well-developed Ordovician–Carboniferous volcanic rocks, granites and mafic–ultramafic intrusions and contains only few porphyry Cu and Au prospects. The Jueluotage belt is characterized by Paleozoic volcanic and sedimentary rocks that are intruded by voluminous Carboniferous–Permian felsic and mafic–ultramafic complexes (Zhou et al., 2010; Gao et al., 2015; Wang et al., 2015a, 2016a). The Central Tianshan block is comprised of Precambrian basement and hosts some hydrothermal magnetite deposits (Bgmrxuar, 1993; Qin et al., 2011; Shen et al., 2014). The main structures of eastern Tianshan are characterized by a series of approximately EW-trending faults including the Daccaotan, Kanggur, Yamansu and Aqikuduke faults (Fig. 1C; Ma et al., 1993; Huang et al., 2013; Wang et al., 2015d).

The Jueluotage belt can be subdivided into the Wutongwozi–Xiaorequanzi and Dananhu–Tousuquan arcs in the north, the Kanggur–Huangshan ductile shear zone in the center and the Aqishan–Yamansu arc in the south, which are separated by the Kanggur and Yamansu faults (Fig. 1C). The lithologies exposed in the study area include the Lower Carboniferous Kushui, Yamansu and Gandun formations (Zhang et al., 2003, 2008; Xiao et al., 2013; Wang et al., 2016b). The Kushui Formation is composed of mainly turbiditic graywacke and sandstone. The Yamansu Formation comprises a suite of intermediate to felsic calc-alkaline volcanic lavas, pyroclastic and sedimentary rocks. The Gandun Formation is composed of turbidites with minor limestone and volcanic rocks.

Widespread intrusive and subvolcanic rocks including diorite porphyry, quartz diorites, plagiogranites, monzogranites, syenogranites

and mafic–ultramafic bodies were primarily emplaced during the Silurian to Permian (Zhou et al., 2010; Su et al., 2012; Zhang et al., 2015a; Zhao et al., 2015) and are located in a nearly EW-trending band along the Dananhu–Tousuquan arc (Fig. 1C). In the Dananhu–Tousuquan arc, EW-trending faults include the Dacotan and Kanggur faults. NW and NE trending faults are also found in the region (Shen et al., 2014; Gao et al., 2015). Several porphyry Cu deposits (e.g., Fuxing, Tuwu, Yandong, Linglong and Chihu) were formed along the southern margin of the Dananhu–Tousuquan arc; such deposits are mainly related to plagiogranite porphyries as well as to deep faults (Fig. 1C).

2.2. Ore deposit geology

The Yuhai porphyry Cu–Mo deposit is situated in the eastern part of the Dananhu–Tousuquan arc belt, approximately 120 km southeast of the Hami City, Xinjiang (Fig. 1C). It is hosted by intermediate-felsic intrusions and volcanic rocks and is located approximately 3–5 km north of the Kanggur fault. The major structures at the Yuhai deposit are NE-trending ductile shear faults that are the secondary faults of the Kanggur–Huangshan ductile shear zone, whereas EW-trending structures are also present within the area (Fig. 2A, B).

In the northern Yuhai area, the rocks contain Lower Carboniferous Wutongwozi Formation spilite-keratophyric series and Neogene Putaogou Formation and Quaternary sediments (Fig. 2A; Zang, 2014; Wei, 2015). In the southern Yuhai area, various granitoid intrusions occur as stocks and dikes that cover an area of approximately 2 km² (Fig. 2A). These intrusions are mainly composed of diorite, granodiorite, diorite porphyry, dacite porphyry and alkali-feldspar granite. Diorite and granodiorite are the primary components of the host rocks in the deposit (Fig. 3A, B). In the study area, the diorite and granodiorite generally exhibit low or moderate degrees of alteration (Fig. 4A, B). The diorite is light gray to gray-white in color and has a microgranular or aphanitic groundmass (Fig. 4A). It exhibits a massive structure that consists of plagioclase (~50%), hornblende (~15%), quartz (~20%), and biotite (~10%) with accessory magnetite, apatite and zircon. The plagioclase is

characterized by a hypidiomorphic, tabular texture with polysynthetic twinning (Fig. 4C). The hornblende is dominated by a xenomorphic tabular texture. The biotite is mainly yellow-brown in color with a hypidiomorphic–xenomorphic flaky or fragmental texture. The light gray granodiorite is primarily composed of plagioclase (~45%), hornblende (~20%), quartz (~25%) and biotite (~5%) with accessory magnetite, apatite and zircon. The plagioclase is dominated by oligoclase and andesine and is hypidiomorphic–xenomorphic (Fig. 4D), whereas the hornblende is characterized by a hypidiomorphic, tabular texture.

In the Yuhai porphyry Cu–Mo deposit, 16 buried orebodies have been identified (Fig. 3A, B) that contain more than 0.3 Mt Cu and 3870 t Mo (Zang, 2014; Wei, 2015) and are still in the exploration stage. The orebodies mainly occur as veins that are 100–1500 m long and 1–44 m thick and dip toward the south at an angle of 10°. In the dipping direction, the explored orebodies extend down-dip for more than 600 m (Wei, 2015), and the Cu–Mo mineralization occurs predominantly in diorite and granodiorite. Sulfide mineralization in the Yuhai deposit occurs as both disseminations and veinlets (Fig. 4E, F). The ore minerals are dominated by chalcopyrite and pyrite (Fig. 4G) with minor molybdenite, bornite, sphalerite (Fig. 4H), malachite, hematite and chalcocite. The gangue minerals are composed of quartz, sericite, and chlorite with minor biotite, epidote and calcite.

The Yuhai deposit shows a zonation of alteration and mineralization, which is the case for the majority of porphyry deposits. The Cu–Mo mineralization is associated with potassic, chlorite–sericite, phyllic and propylitic alteration in diorite and granodiorite. The lack of potassic alteration at the surface within the deposit indicates that the area has undergone minimal erosion and that the deposit is largely preserved. Based on the alteration mineral assemblages and ore fabrics as well as on crosscutting relationships, the Cu–Mo mineralization of the Yuhai deposit can be divided into four stages. Stage I is characterized by vein-like and disseminated mineralization associated with potassic alteration with an assemblage of quartz + pyrite. Stage II is represented by vein stockworks containing quartz + pyrite + chalcopyrite associated with chlorite–sericite–phyllic alteration. Stage III is characterized by

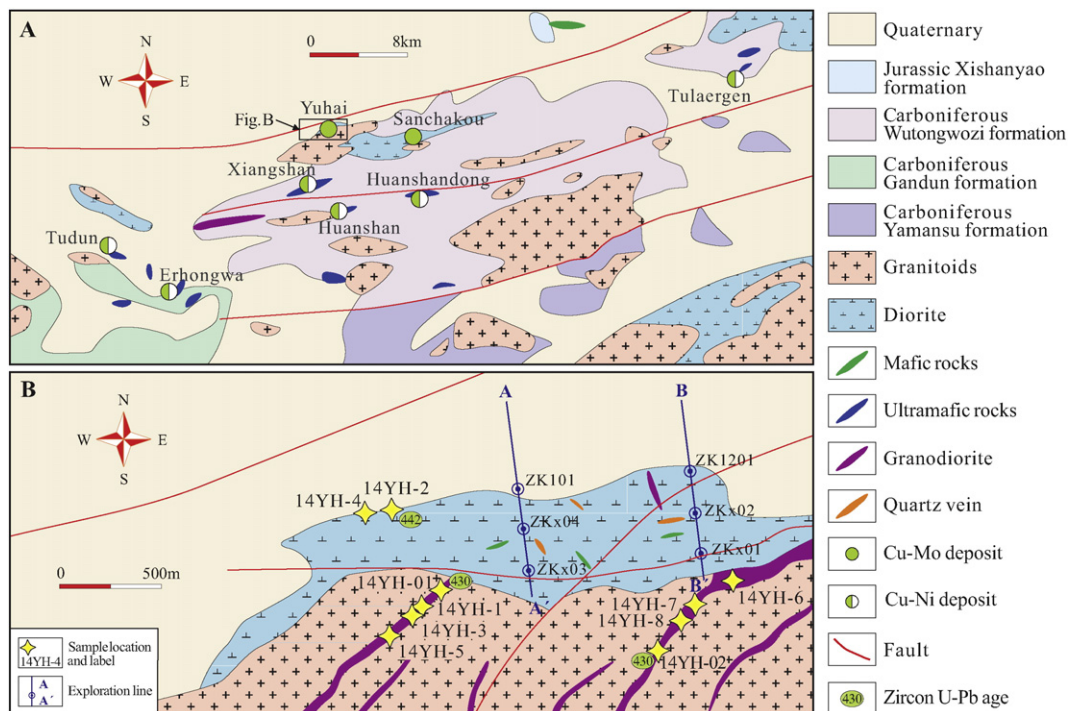


Fig. 2. (A) Geological map of the Yuhai region showing the distribution of Cu and Cu–Ni deposits. (B) Simplified geological map of the Yuhai porphyry Cu–Mo deposit. Panel A is modified from Zang (2014). Panel B is modified from Zang (2014).

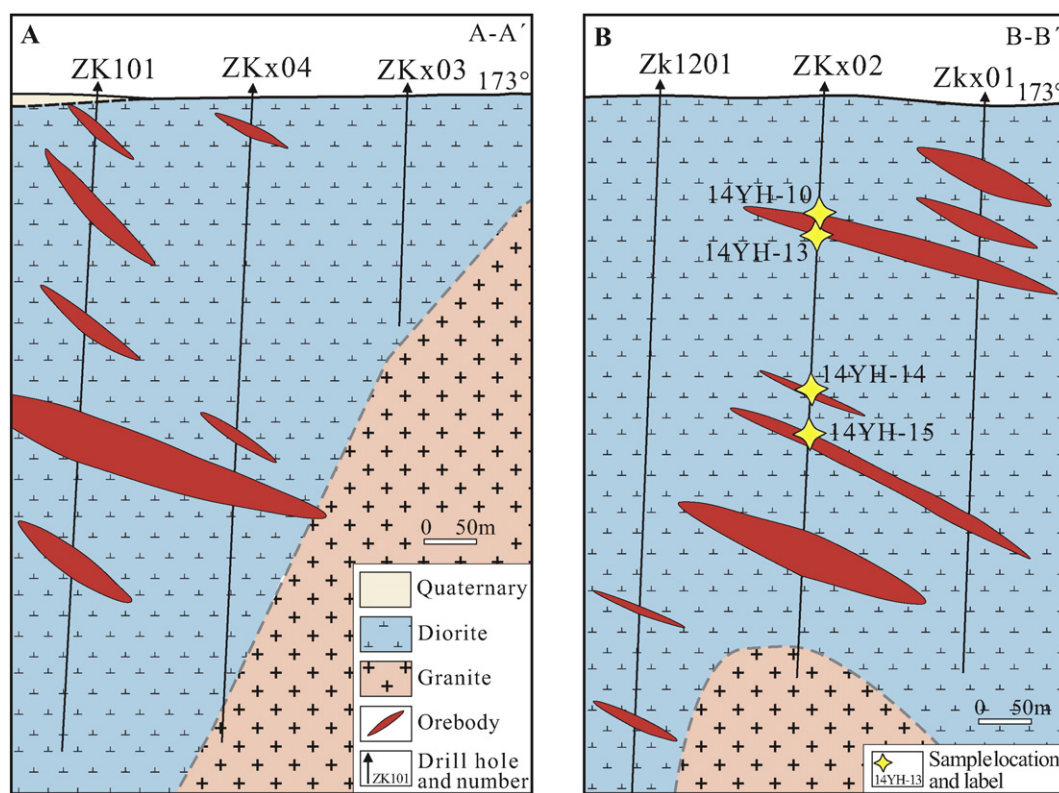


Fig. 3. Geological section of the A–A' and B–B' exploration lines across the Yuhai porphyry Cu–Mo deposit. Modified from Zang (2014).

an assemblage of quartz + chalcopyrite + molybdenite occurring as veins or disseminations in hosting rocks. Stage IV consists of carbonates (calcite) and minor sulfides. Stage III and Stage IV are commonly associated with phyllic alteration (Zang, 2014; Wei, 2015).

3. Sample preparation and analytical methods

3.1. Sample preparation

The intrusive samples in the Yuhai deposit, especially around the ore body, are generally altered to some degree. In this study, the least altered samples from the Yuhai porphyry Cu–Mo deposit were chosen from outcrops at the surface, and the sampling locations are shown in Fig. 2B. One diorite (14YH-1) and two granodiorite (14YH-01 and 14YH-02) samples were collected for LA-ICP-MS zircon U–Pb dating, trace element and in situ Hf isotopic analyses. One diorite sample (14YH-4) and six granodiorite samples (14YH-1, 14YH-8, 14YH-3, 14YH-5, 14YH-6, and 14YH-7) were chosen for major and trace element analysis. In addition, four molybdenite samples (14YH-13, 14YH-14, 14YH-15 and 14YH-10) were collected from the Cu–Mo orebodies of the Yuhai deposit for Re–Os analyses.

3.2. Analytical methods

3.2.1. Zircon U–Pb dating

Zircon concentrates were separated from the diorite and granodiorite samples by using conventional heavy liquids, magnetic separation techniques, and handpicking under a binocular microscope at the Langfang Regional Geological Survey in Hebei Province, China. Zircon grains, together with zircon standard TEMORA-1 and 91500, were mounted in epoxy mounts, which were then polished to section the crystals in half for analysis. Zircons were documented with transmitted and reflected light micrographs as well as cathodoluminescence (CL) images to reveal their internal structures prior to LA-ICP-MS analyses. LA-ICP-MS zircon

U–Pb dating and trace element analyses were synchronously conducted on an Agilent 7500a ICP–MS, equipped with a 193 nm laser ablation system, housed at the State Key Laboratory of Geological Process and Mineral Resources of the China University of Geosciences, Beijing. During the analyses, the laser spot was 10 μm or 23 μm in different samples. The $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ ratios were calculated using GLITTER program, and then corrected using zircon TEMORA-1 as an external standard. The detailed analytical procedures are similar to those described by Yuan et al. (2004) and Wu et al. (2006a). Error on individual analysis by LA-ICP-MS is quoted at the 1 σ confidence level. The results were processed using the ISOPLOT software (Ludwig, 2003).

3.2.2. Whole rock major and trace element compositions

Whole-rock compositions of the diorite and granodiorite samples were analyzed at the Beijing Nuclear Industry Geological Analysis and Test Center. Major element analysis was conducted using a Philips PW2404 XRF with testing precision greater than 1%. Trace element analysis was performed using a Finnigan MAT Element I ICP-MS, with RSD (10 min) <1% and RSD (4 h) <5%. For the testing methods, please refer to Gao et al. (2002).

3.2.3. Hf isotopic analyses

In situ zircon Hf isotopic analyses were measured using a Neptune MC-ICP-MS, equipped with a Geolas 193 nm laser-ablation system at the Institute of Geology and Geophysics, Chinese Academy of Science in Beijing. Depending on the zircon size, a stationary beam spot with spot size of approximately 60 μm was employed for the analyses, and the international standard zircon sample GJ-1 was used as a reference. Raw count rates for ^{172}Yb , ^{173}Yb , ^{175}Yb , ^{175}Lu , $^{176}(\text{Hf} + \text{Yb} + \text{Lu})$, ^{177}Hf , ^{178}Hf , ^{179}Hf , ^{180}Hf and ^{182}W were collected and isobaric interference corrections for ^{176}Lu and ^{176}Yb on ^{176}Hf must be determined precisely. Details on the instrumental conditions and data acquisition are given in Wu et al. (2006a). The measured values of the well-characterized zircon standard (GJ-1) agreed with the recommended

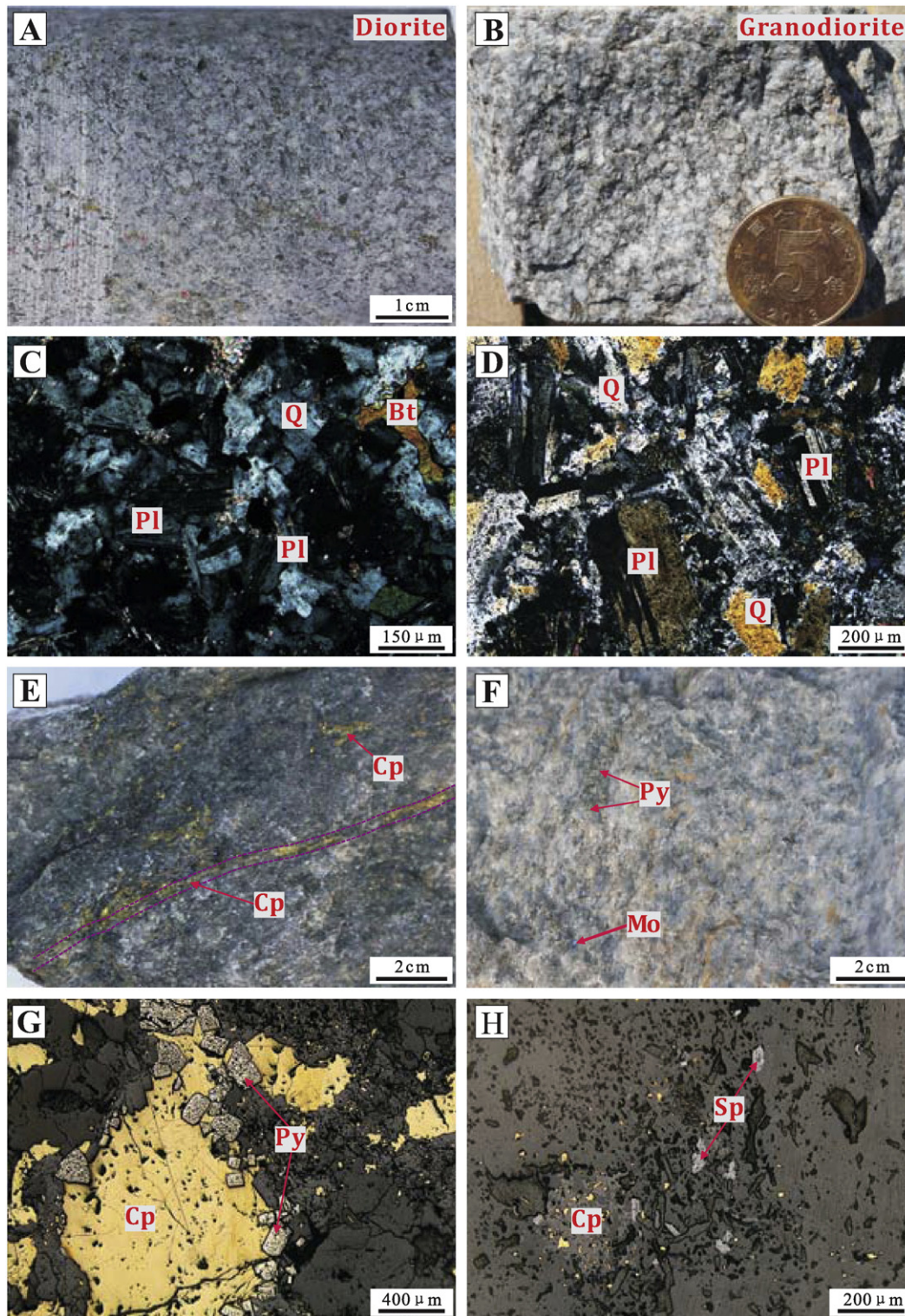


Fig. 4. Photographs and photomicrographs showing the mineralogy of intrusions and mineralization features of the Yuhai porphyry Cu–Mo deposit. (A) Hand specimen of diorite; (B) hand specimen of granodiorite; (C) photomicrograph of diorite, showing plagioclase quartz and biotite, under crossed-polarized light; (D) photomicrograph of granodiorite, showing hypidiomorphic-xenomorphic plagioclase and quartz, under crossed-polarized light; (E) fine-grained chalcopyrite vein and scattered chalcopyrite in altered diorite; (F) disseminated pyrite and molybdenite in altered granodiorite; (G) anhedral chalcopyrite and euhedral-subhedral pyrite assemblages, under reflected light; (H) sulphides assemblage showing anhedral chalcopyrite and sphalerite, under reflected light. Abbreviations: Q – quartz; Bt – biotite; Pl – plagioclase; Cp – chalcopyrite; Py – Pyrite; Mo – molybdenite; Sp – sphalerite.

values to within 2σ . The weighted average of the $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of the GJ-1 zircon samples was 0.282006 ± 0.000006 (2σ , $n = 71$), consistent with the recommended values (Elhlou et al., 2006) to within 2σ . The initial $^{176}\text{Lu}/^{177}\text{Hf}$ ratios were calculated by using a decay constant of $1.867 \times 10^{-11} \text{ year}^{-1}$ for ^{176}Lu (Soderlund et al., 2004). The chondritic

values of the $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.0332 and $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.282772 (Blichert-Toft and Albarède, 1997) were adopted to calculate the $\varepsilon_{\text{Hf}}(t)$ values. The T_{DM} (depleted mantle model age) was measured in reference to the depleted mantle at a present-day $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.0384 and $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.28325 (Griffin et al., 2002). The

Table 1
LA-ICP-MS zircon U–Pb data for the Yuhai diorite and granodiorite in eastern Tianshan.

Spot	Element (ppm)			Th/U	Isotope ratio				Apparent age (Ma)							
	Pb*	U	Th		²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	± 1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ
<i>14YH-2, diorite, 24 spots (without spot 06), weighted mean age = 441.6 ± 2.5 Ma, MSWD = 0.03</i>																
01	12	172	67	0.39	0.05571	0.00158	0.54355	0.01509	0.07074	0.00096	441	38	441	10	441	6
02	7	97	29	0.30	0.05595	0.00211	0.54675	0.02019	0.07086	0.00103	450	56	443	13	441	6
03	11	149	63	0.42	0.05572	0.00176	0.54473	0.01699	0.07089	0.00095	441	46	442	11	442	6
04	7	102	28	0.28	0.05581	0.00241	0.55042	0.02322	0.07151	0.00110	445	66	445	15	445	7
05	15	213	95	0.45	0.05544	0.00168	0.54232	0.01624	0.07093	0.00094	430	43	440	11	442	6
06	16	226	105	0.46	0.05536	0.00177	0.52798	0.01662	0.06916	0.00093	427	46	430	11	431	6
07	12	167	63	0.38	0.05574	0.00183	0.54456	0.01762	0.07084	0.00095	442	48	441	12	441	6
08	8	117	42	0.35	0.05624	0.00235	0.55054	0.02275	0.07098	0.00098	462	67	445	15	442	6
09	6	83	26	0.32	0.05581	0.00231	0.54582	0.02223	0.07091	0.00104	445	64	442	15	442	6
10	10	146	41	0.28	0.05533	0.00203	0.54112	0.01958	0.07091	0.00095	426	57	439	13	442	6
11	12	167	64	0.38	0.05595	0.00171	0.54531	0.01634	0.07067	0.00095	450	43	442	11	440	6
12	7	99	34	0.34	0.05573	0.00324	0.54316	0.03101	0.07067	0.00119	442	97	441	20	440	7
13	10	145	61	0.42	0.05553	0.00204	0.54294	0.01965	0.07089	0.00097	434	56	440	13	442	6
14	12	178	54	0.30	0.05571	0.00155	0.54503	0.01488	0.07093	0.00093	441	38	442	10	442	6
15	8	110	35	0.32	0.05558	0.00207	0.54138	0.01979	0.07063	0.00100	436	56	439	13	440	6
16	3	43	11	0.25	0.05561	0.00499	0.54458	0.04809	0.07100	0.00145	437	162	441	32	442	9
17	8	119	35	0.30	0.05564	0.00215	0.54436	0.02055	0.07093	0.00104	438	58	441	14	442	6
18	3	48	15	0.31	0.05562	0.00507	0.54439	0.04915	0.07096	0.00129	437	170	441	32	442	8
19	8	110	39	0.35	0.05597	0.00284	0.54757	0.02732	0.07093	0.00109	451	83	443	18	442	7
20	9	126	49	0.39	0.05553	0.00189	0.54269	0.01806	0.07086	0.00101	434	49	440	12	441	6
21	7	102	48	0.47	0.05551	0.00255	0.54100	0.02442	0.07067	0.00105	433	74	439	16	440	6
22	12	171	70	0.41	0.05555	0.00213	0.54204	0.02044	0.07074	0.00100	434	59	440	13	441	6
23	12	167	61	0.36	0.05577	0.00287	0.54758	0.02791	0.07118	0.00103	443	88	443	18	443	6
24	7	94	37	0.39	0.05561	0.00320	0.54516	0.03088	0.07108	0.00115	437	97	442	20	443	7
25	6	78	41	0.53	0.05573	0.00337	0.54713	0.03255	0.07118	0.00116	442	104	443	21	443	7
<i>14YH-01, granodiorite, 19 spots (without spots 01, 12, 13, 14, 23, and 24), weighted mean age = 430.4 ± 2.9 Ma, MSWD = 0.04</i>																
01	8	68	27	0.40	0.19030	0.00503	2.07942	0.05192	0.07924	0.00118	2745	22	1142	17	492	7
02	5	62	27	0.43	0.05542	0.00263	0.52659	0.02456	0.06890	0.00102	429	77	430	16	430	6
03	7	99	51	0.51	0.05523	0.00205	0.52608	0.01910	0.06908	0.00097	422	56	429	13	431	6
04	9	122	62	0.51	0.05558	0.00249	0.53094	0.02351	0.06927	0.00097	436	74	432	16	432	6
05	3	47	20	0.42	0.05557	0.00365	0.53088	0.03419	0.06927	0.00123	435	112	432	23	432	7
06	7	103	34	0.33	0.05833	0.00259	0.55729	0.02440	0.06928	0.00097	542	71	450	16	432	6
07	7	91	33	0.36	0.05580	0.00245	0.53174	0.02293	0.06911	0.00101	444	70	433	15	431	6
08	6	83	19	0.23	0.05568	0.00288	0.53067	0.02700	0.06912	0.00106	440	86	432	18	431	6
09	7	95	27	0.29	0.05550	0.00332	0.52764	0.03115	0.06894	0.00107	432	104	430	21	430	6
10	4	60	16	0.26	0.05505	0.00470	0.52020	0.04392	0.06853	0.00123	414	158	425	29	427	7
11	10	132	52	0.40	0.05550	0.00287	0.52811	0.02687	0.06900	0.00103	432	87	431	18	430	6
12	12	138	40	0.29	0.06516	0.00588	0.56140	0.04974	0.06249	0.00105	779	197	452	32	391	6
13	12	122	47	0.39	0.06009	0.00577	0.60683	0.05738	0.07325	0.00125	607	216	482	36	456	8
14	5	60	18	0.30	0.05721	0.00934	0.56311	0.09144	0.07137	0.00150	500	324	454	59	444	9
15	7	101	28	0.28	0.05536	0.00477	0.52606	0.04501	0.06891	0.00112	427	164	429	30	430	7
16	12	156	71	0.46	0.05565	0.00268	0.52889	0.02512	0.06891	0.00101	438	80	431	17	430	6
17	7	93	25	0.27	0.05545	0.00566	0.52765	0.05341	0.06900	0.00123	430	196	430	36	430	7
18	4	54	13	0.25	0.05598	0.00593	0.52913	0.05517	0.06854	0.00155	452	194	431	37	427	9
19	5	72	18	0.25	0.05591	0.00357	0.52914	0.03313	0.06863	0.00124	449	107	431	22	428	7
20	7	104	32	0.31	0.05535	0.00390	0.52828	0.03673	0.06921	0.00117	426	126	431	24	431	7
21	5	75	30	0.40	0.05552	0.00493	0.52931	0.04649	0.06914	0.00123	433	166	431	31	431	7
22	7	94	39	0.41	0.05521	0.00440	0.52599	0.04147	0.06909	0.00115	421	148	429	28	431	7
23	6	60	16	0.27	0.13934	0.00885	1.53544	0.09441	0.07991	0.00165	2219	78	945	38	496	10
24	11	141	48	0.34	0.07438	0.00329	0.74967	0.03259	0.07309	0.00108	1052	64	568	19	455	6
25	8	110	32	0.29	0.05525	0.00348	0.52571	0.03252	0.06899	0.00121	422	107	429	22	430	7
<i>14YH-02, granodiorite, 24 spots (without spot 09), weighted mean age = 430.3 ± 2.6 Ma, MSWD = 0.09</i>																
01	9	123	43	0.35	0.05536	0.00270	0.52885	0.02530	0.06926	0.00104	427	80	431	17	432	6
02	6	83	22	0.27	0.05579	0.00310	0.53224	0.02916	0.06916	0.00105	444	95	433	19	431	6
03	6	87	37	0.42	0.05529	0.00220	0.52781	0.02045	0.06921	0.00105	424	59	430	14	431	6
04	8	112	42	0.37	0.05559	0.00202	0.52808	0.01877	0.06887	0.00095	436	54	431	12	429	6
05	4	50	16	0.32	0.05560	0.00312	0.53148	0.02914	0.06931	0.00117	436	92	433	19	432	7
06	8	110	48	0.44	0.05918	0.00250	0.56475	0.02346	0.06919	0.00099	574	65	455	15	431	6
07	5	72	19	0.26	0.05532	0.00256	0.52840	0.02391	0.06926	0.00106	425	73	431	16	432	6
08	5	79	20	0.26	0.05523	0.00332	0.51723	0.03063	0.06790	0.00107	422	104	423	20	423	6
09	4	54	19	0.35	0.05602	0.00360	0.55040	0.03468	0.07124	0.00123	453	109	445	23	444	7
10	6	85	23	0.27	0.05527	0.00298	0.52632	0.02789	0.06905	0.00108	423	90	429	19	430	7
11	6	88	27	0.31	0.05537	0.00225	0.52655	0.02090	0.06895	0.00102	427	62	430	14	430	6
12	8	119	32	0.27	0.05539	0.00249	0.52700	0.02331	0.06898	0.00098	428	73	430	16	430	6
13	4	63	19	0.30	0.05576	0.00359	0.53035	0.03363	0.06896	0.00114	443	112	432	22	430	7
14	16	222	100	0.45	0.05554	0.00170	0.52882	0.01570	0.06904	0.00094	434	42	431	10	430	6
15	11	144	61	0.42	0.05566	0.00303	0.52967	0.02837	0.06899	0.00106	439	92	432	19	430	6
16	6	78	18	0.23	0.05547	0.00358	0.52788	0.03352	0.06900	0.00116	431	112	430	22	430	7
17	10	142	50	0.35	0.05569	0.00281	0.53178	0.02623	0.06924	0.00111	440	81	433	17	432	7
18	6	88	20	0.23	0.05570	0.00490	0.53088	0.04619	0.06911	0.00121	440	164	432	31	431	7

(continued on next page)

Table 1 (continued)

Spot	Element (ppm)			Th/U	Isotope ratio						Apparent age (Ma)					
	Pb*	U	Th		$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ
19	8	106	31	0.29	0.05553	0.00381	0.52751	0.03562	0.06888	0.00118	434	120	430	24	429	7
20	4	61	17	0.28	0.05546	0.00487	0.52779	0.04563	0.06901	0.00134	431	160	430	30	430	8
21	7	96	29	0.30	0.05539	0.00358	0.52683	0.03339	0.06897	0.00118	428	111	430	22	430	7
22	4	58	18	0.31	0.05554	0.00693	0.53026	0.06565	0.06922	0.00138	434	243	432	44	431	8
23	11	150	71	0.48	0.05554	0.00251	0.52964	0.02341	0.06915	0.00103	434	72	432	16	431	6
24	8	104	30	0.29	0.05577	0.00405	0.52919	0.03775	0.06880	0.00127	443	126	431	25	429	8
25	7	92	42	0.46	0.05533	0.00326	0.52979	0.03050	0.06943	0.00118	426	98	432	20	433	7

T_{DM}^{C} (crustal model age) was calculated using an average continental crustal $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.015 (Griffin et al., 2002).

3.2.4. Re–Os isotopic analyses

Molybdenite was magnetically separated and then handpicked under a binocular microscope. Sample preparation and mineral separation followed techniques outlined by Shirey and Walker (1995), Mao

et al. (1999), and Du et al. (2004). Re–Os isotopic analyses were carried out at the Re–Os Laboratory of National Research Center of Geoanalysis, Chinese Academy of Geological Sciences, Beijing. Re–Os isotopic data were obtained by isotope dilution ICP–MS (TJA X-series ICP–MS). The decay constant used in the age calculation was $\lambda^{187}\text{Re} = 1.666 \times 10^{-11} \text{ year}^{-1}$ (Smoliar et al., 1996). Uncertainty in Re–Os model ages includes 1.02% uncertainty in the ^{187}Re decay constant and uncertainty

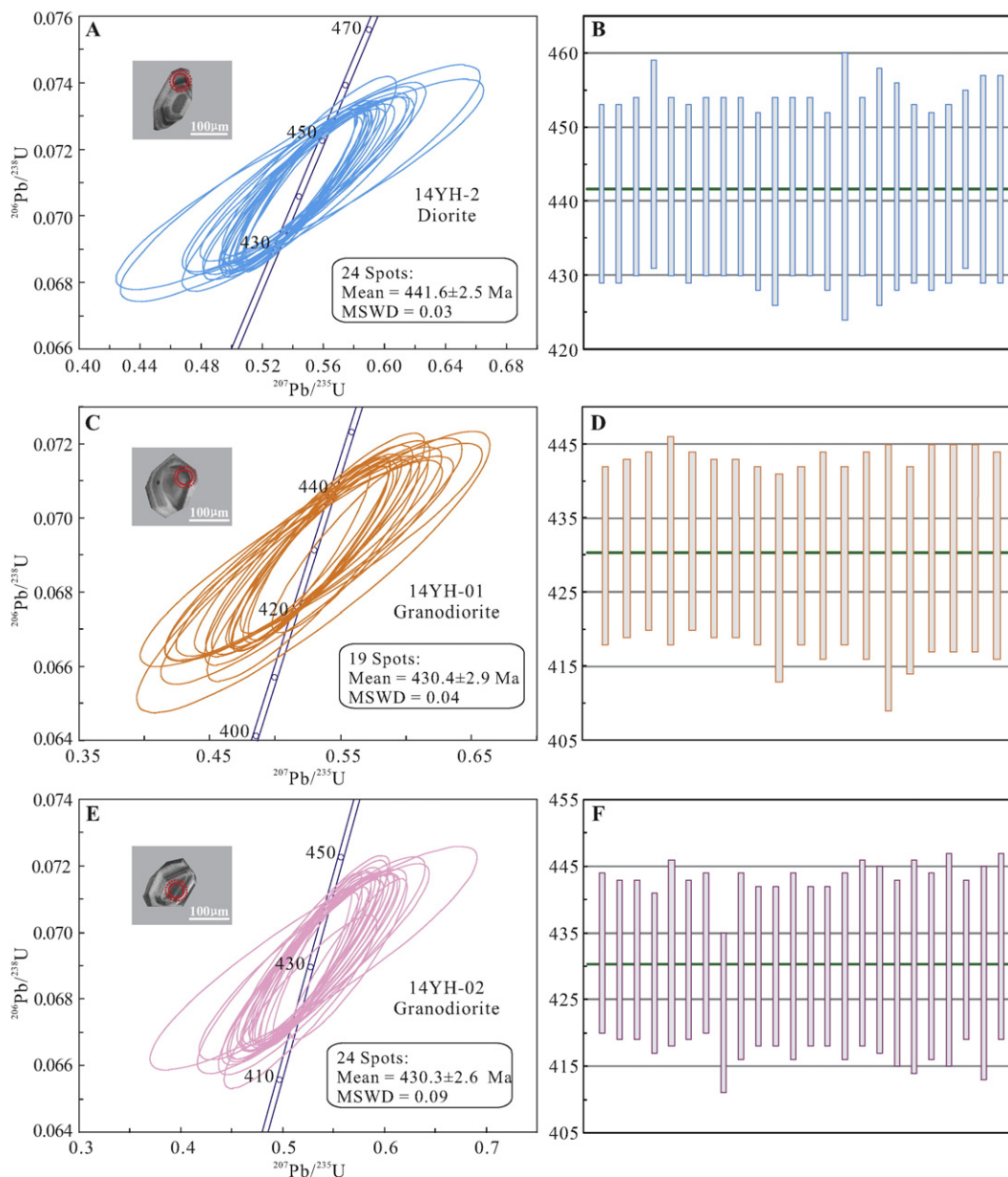


Fig. 5. Cathodoluminescence images, concordia and weighted diagrams of the zircon U–Pb age of the diorite (A and B) and granodiorite (C, D, E and F) in the Yuhai porphyry Cu–Mo deposit.

Table 2

Zircon trace element data for the Yuhai diorite and granodiorite in eastern Tianshan.
 Chondrite REE values are after Sun and McDonough (1989).

Spot	Ti	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Th	U	Pb	Th/U	(La/Yb) _{chn}	Eu/Eu*	Ce/Ce*	T	
<i>14YH-2, diorite</i>																										
01	7.31	1124	0.057	22.4	0.095	1.48	3.42	1.6	17.35	7.04	91.67	38.96	190.9	54.4	690.4	161.78	7910	67	172	12.1	0.39	0.00006	0.64	74.63	714	
02	7.11	757.1	0.051	12.12	0.048	1.02	2.24	1.151	11.68	4.42	60.26	26.56	137	39.35	519.7	127.40	7613	29	97	6.7	0.30	0.00007	0.69	60.06	712	
03	7.1	1196	0.076	18.86	0.17	3.04	5.56	2.38	22.53	8.11	103.5	42.89	209.1	57.93	726.6	174.68	7500	63	149	10.6	0.42	0.00008	0.65	40.68	712	
04	6.91	760.8	0.066	12.32	0.069	1.2	2.14	1.268	11.45	4.48	60.99	26.89	141.3	40.62	532.8	136.49	7730	28	102	7.0	0.28	0.00009	0.78	44.76	709	
05	7.79	1390	0.083	25.86	0.116	2.89	5.11	2.32	24.96	9.54	119.3	48.99	239.5	65.93	821.3	191.95	7979	95	213	15.3	0.45	0.00007	0.63	64.62	719	
06	10.1	1386	0.108	27.54	0.086	1.77	4.32	2.09	23.96	9.13	119.3	49.48	243.5	67.6	862.9	201.43	7621	105	226	15.9	0.46	0.00009	0.63	70.06	741	
07	9.16	1166	0.067	19.88	0.083	1.74	3.16	1.66	16.56	6.77	93.08	40.97	207.2	58.98	759.3	188.67	8449	63	167	11.8	0.38	0.00006	0.70	65.36	733	
08	6.33	796.2	0.082	15.09	0.058	1.11	2.28	1.236	12.8	5.19	68.83	29.18	146.3	42.23	547.6	128.79	7720	42	117	8.3	0.35	0.00011	0.70	53.65	702	
09	6.78	569.5	7.56	23.49	1.93	8.69	3.43	1.217	10.13	3.68	46.96	19.82	100.7	28.7	381.5	90.25	7007	26	83	5.8	0.32	0.01422	0.63	1.51	708	
10	7.76	876.4	0.278	17.08	0.426	5.07	4.42	1.54	14.27	5.16	68.99	30.11	157.1	45.65	613.2	147.83	7329	41	146	10.1	0.28	0.00033	0.59	12.17	719	
11	8.45	1130	0.061	20.48	0.07	1.54	3.15	1.53	17.39	6.98	94.82	39.81	199.7	56.32	735	168.49	7226	64	167	11.9	0.38	0.00006	0.63	76.84	726	
12	6.43	865	0.124	12.25	0.17	2.69	5.13	1.67	20.64	6.71	77.33	28.78	137.8	37.71	473	114.91	7164	34	99	6.9	0.34	0.00019	0.50	20.69	703	
13	8.54	1091	0.067	19.8	0.091	1.07	2.6	1.7	18.16	7.16	92.6	38.79	188.7	52.62	681.3	155.79	7004	61	145	10.4	0.42	0.00007	0.76	62.17	727	
14	7.87	1034	0.076	18.72	0.059	1.42	3.15	1.47	14.66	5.67	80.84	36.55	189.6	55.43	733.1	171.97	7358	54	178	12.5	0.30	0.00007	0.66	68.54	720	
15	7.18	658.5	0.074	12.2	0.05	0.8	2.27	0.953	9.85	3.76	51.05	22.19	111.6	32.6	434.5	104.04	7189	35	110	7.7	0.32	0.00012	0.62	49.17	713	
16	4.77	364.6	0.089	5.63	0.069	0.56	1.54	0.613	5.94	2.21	28.26	11.84	59.13	17.32	241.9	57.03	8187	11	43	3.0	0.25	0.00026	0.62	17.61	680	
17	6.56	759.1	0.085	13.71	0.05	1.17	2.4	1.184	11.29	4.22	58.97	25.85	132.7	39.23	542.2	126.16	7526	35	119	8.4	0.30	0.00011	0.70	51.56	705	
18	5.3	418.5	0.113	6.08	0.063	0.91	1.61	0.718	6.87	2.76	33.77	13.16	64.33	18.34	247.4	59.60	7420	15	48	3.4	0.31	0.00033	0.66	17.67	688	
19	6.57	771.4	0.119	12.72	0.073	0.77	1.97	1.116	12.08	4.4	59.35	25.43	125.7	34.98	472.2	114.22	7337	39	110	7.9	0.35	0.00018	0.70	33.46	705	
20	6.98	902.3	0.062	14.01	0.091	1.81	3.44	1.77	17.19	6.33	79.39	32.66	161.3	45.98	596.5	140.80	6935	49	126	9.1	0.39	0.00007	0.70	45.73	710	
21	5.3	641.7	0.091	9.19	0.075	2.16	3.91	1.63	15.01	4.79	56.81	20.99	97.14	26.8	344.2	77.00	8632	48	102	7.4	0.47	0.00019	0.65	27.27	688	
22	8.19	1243	0.109	21.92	0.108	1.81	4.05	2.03	20.75	8	105	44.99	219.1	61.53	784.4	180.42	7087	70	171	12.4	0.41	0.00010	0.68	49.53	724	
23	11.1	1128	0.145	20.51	0.091	1.17	3.24	1.76	17.93	7	95.14	40.07	199.4	57.15	748.5	171.55	7433	61	167	12.0	0.36	0.00014	0.71	43.78	750	
24	5.46	490.6	0.113	11.25	0.08	0.66	1.42	0.898	7.63	3.06	39.67	16.33	78.73	22.43	294.4	68.70	7923	37	94	6.9	0.39	0.00028	0.83	29.01	690	
25	8.12	992.8	0.076	12.53	0.173	3.4	6.86	2.19	26.65	8.72	100.7	37.39	168.3	43.84	507.6	104.86	7591	41	78	5.8	0.53	0.00011	0.50	26.79	723	
<i>14YH-01, granodiorite</i>																										
01	6.01	728.8	0.065	9.33	0.154	2.31	3.85	1.83	16.74	5.69	67.68	25.61	123.8	33.45	423.1	102.75	7857	27	68	7.9	0.40	0.00011	0.70	22.86	698	
02	5.47	704.1	0.055	8.79	0.137	2.59	5.43	2.23	18.97	6.19	70.34	25.78	119.5	31.53	389.4	89.35	7549	27	62	4.6	0.43	0.00010	0.67	24.83	690	
03	8.45	888.3	0.046	14.35	0.225	3.82	6.78	2.04	24.04	7.73	88.7	33.11	147.3	36.95	438.2	93.02	8046	51	99	7.4	0.51	0.00008	0.49	34.58	726	
04	6.12	1118	0.059	15.42	0.26	3.72	7.13	3.21	31.05	9.84	112.6	41.37	188.3	49.5	615.4	142.61	7214	62	122	9.2	0.51	0.00007	0.66	30.53	699	
05	8.94	540	0.063	11.19	0.068	0.86	3.15	0.904	12.72	4.39	52.59	18.42	82.29	21.22	251.4	50.62	8259	20	47	3.5	0.42	0.00018	0.44	41.92	731	
06	7.98	742.2	0.079	11.63	0.056	1.22	2.3	1.166	10.96	4.58	62.08	26.97	139.6	39.1	515.2	119.51	7201	34	103	7.5	0.33	0.00011	0.71	42.87	721	
07	6.16	803.4	0.069	11.49	0.131	2.4	4.47	2.22	18.79	6.18	76.93	29.45	139.4	38.57	491.1	111.77	7369	33	91	6.6	0.36	0.00010	0.74	29.63	700	
08	6.84	676.9	0.079	9.15	0.066	0.87	2.32	1.015	9.57	3.51	48.18	20.72	111.1	32.36	454.6	109.32	7590	19	83	5.8	0.23	0.00012	0.66	31.07	709	
09	6.13	701.5	0.107	12.39	0.091	0.99	2.03	1.063	10.51	4.06	55.65	23.79	120.3	34.84	459.5	110.62	8111	27	95	6.8	0.29	0.00017	0.70	30.79	700	
10	8.37	546.2	0.107	8.38	0.071	0.81	2.05	0.898	8.32	3.23	42.41	17.94	90.33	25.35	344	82.71	7912	16	60	4.2	0.26	0.00022	0.66	23.57	725	
11	6.69	1158	0.087	17.05	0.172	3.47	6.82	2.52	24.32	8.6	108	42.41	203.8	55.6	709.9	162.66	7837	52	132	9.6	0.40	0.00009	0.60	34.17	707	

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Table 2 (continued)

Spot	Ti	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Th	U	Pb	Th/U	(La/Yb) _{chn}	Eu/Eu*	Ce/Ce*	T	
12	7.84	923.2	0.196	14.84	0.127	2.12	3.13	1.33	14.47	5.32	72.31	30.29	154.2	43.02	568.6	132.56	7328	40	138	12.3	0.29	0.00025	0.60	23.06	720	
13	7.59	1056	0.212	15.39	0.135	2.32	4.45	1.92	20.09	7.04	89.15	36	169.2	46.22	604	140.24	7364	47	122	11.9	0.39	0.00025	0.62	22.30	717	
14	8.82	358.6	0.252	7.6	0.165	1.19	1.58	0.53	5.76	1.9	27.66	11.41	58.63	17.05	225.7	54.45	7672	18	60	4.6	0.30	0.00080	0.54	9.14	730	
15	6.57	766.4	0.151	12.31	0.096	1.37	2.41	1.185	11.09	4.27	56.98	24.5	126.7	36.02	490.6	114.59	7500	28	101	7.0	0.28	0.00022	0.70	25.07	705	
16	8.07	1136	0.078	20.67	0.097	1.29	3.51	1.81	20.56	7.75	98.62	38.79	188.9	51.84	654.3	150.38	7082	71	156	11.5	0.46	0.00009	0.65	58.26	722	
17	4.99	668.5	0.184	9.76	0.112	0.93	2.41	1.35	11.62	3.96	53.94	21.43	108.8	30.78	413.9	99.85	7518	25	93	6.6	0.27	0.00032	0.78	16.67	683	
18	16.8	467.2	0.123	6.35	0.068	0.9	0.87	0.863	7.39	2.89	37.73	15.16	79.11	22.14	312	74.28	7106	13	54	3.9	0.25	0.00028	1.04	17.02	789	
19	6.57	671.7	0.069	9.64	0.047	1.03	1.8	1.022	9.88	3.59	51.06	21.65	111.3	31.98	427.6	102.57	6999	18	72	5.0	0.25	0.00012	0.74	41.50	705	
20	5.8	452.1	0.131	10.54	0.119	1.06	1.82	0.806	7.36	2.76	34.84	14.81	73.85	21.4	294.3	70.83	8005	32	104	7.5	0.31	0.00032	0.67	20.70	695	
21	4.8	789.4	0.179	9.5	0.17	2.89	4.34	2.23	18.43	6.31	72.08	27.17	124.5	33.86	437.7	95.08	7513	30	75	5.5	0.40	0.00029	0.76	13.35	680	
22	6.01	890.3	0.159	11.89	0.136	2.83	5.59	2.47	20.71	6.7	78.49	29.8	137.4	37.06	489.1	108.53	7047	39	94	7.0	0.41	0.00023	0.70	19.82	698	
23	7.55	495.8	0.139	8.24	0.126	0.9	1.24	0.955	7.19	2.7	38.02	15.51	79.28	22.55	308.2	71.95	7080	16	60	6.5	0.27	0.00032	0.98	15.27	717	
24	9.28	1147	0.146	18.83	0.104	1.36	2.65	1.43	17.28	6.84	92.99	39.47	197.3	55.05	718.6	161.70	6700	48	141	11.5	0.34	0.00015	0.65	37.47	734	
25	7.6	846	0.098	13.14	0.081	0.84	2.75	1.18	11.84	4.98	66.56	28.5	139.6	41.14	547.5	126.25	7153	32	110	7.8	0.29	0.00013	0.63	36.16	717	
<i>14YH-02, granodiorite</i>																										
01	6.26	744.1	0.076	14.4	0.081	1.04	2.83	1.13	12.84	4.48	61.97	26.22	134.2	38.75	505.8	122.55	8287	43	123	8.9	0.35	0.00011	0.57	45.00	701	
02	6.25	597.2	0.064	10.24	0.056	0.91	1.86	0.951	10.18	3.79	50.3	21.54	109.4	32.72	436.7	104.73	8047	22	83	5.9	0.27	0.00011	0.67	41.94	701	
03	9.66	931.4	0.041	14.36	0.125	2.55	5.23	1.72	21.16	7.56	90.84	34.79	164.2	43.08	519.5	114.42	7712	37	87	6.3	0.42	0.00006	0.50	49.18	738	
04	6.01	928.5	0.043	13.82	0.104	1.63	4.08	1.91	18.63	6.47	83.59	33.48	167	46.88	610.7	146.33	7120	42	112	8.1	0.37	0.00005	0.67	50.67	698	
05	6.19	404.4	0.042	6.65	0.033	0.638	1.21	0.57	6.45	2.38	31.34	13.02	66.62	19.34	263	63.81	7991	16	50	3.6	0.32	0.00011	0.62	43.80	700	
06	5.79	1038	0.088	14.85	0.229	4.12	6.4	2.75	25.85	8.8	101.8	39.73	183.7	49.16	613.9	141.69	7670	48	110	8.2	0.44	0.00010	0.65	25.65	695	
07	6.35	525.9	0.054	8.83	0.047	0.52	1.7	0.865	8.68	3.1	40.51	17.71	92.22	26.58	360.8	86.32	7656	19	72	5.1	0.26	0.00011	0.69	42.97	702	
08	6.54	588.1	0.087	9.25	0.074	1.05	2.02	0.895	9.74	3.43	46.05	19.73	103.5	30.57	410.4	100.18	7590	20	79	5.5	0.26	0.00015	0.62	28.27	705	
09	5.74	529.3	0.076	7.45	0.106	1.57	2.96	1.4	12.05	4.08	48.5	18.23	88.3	24.46	318.4	73.95	7448	19	54	4.1	0.35	0.00017	0.72	20.35	694	
10	6.92	642.2	0.074	10.84	0.058	0.88	2.04	1.07	10.71	3.91	53.01	22.37	118.5	33.78	456	109.33	7666	23	85	6.0	0.27	0.00012	0.70	40.57	709	
11	6.24	703.3	0.044	11.04	0.04	1.13	2.83	1.26	12.72	4.74	62.66	25.26	125.4	35.25	463	108.13	6672	27	88	6.3	0.31	0.00007	0.64	64.52	701	
12	6.22	710.1	0.113	12.32	0.067	0.8	2.24	1.17	10.79	4.31	56.84	24.71	125.9	36.8	490.1	117.19	7765	32	119	8.4	0.27	0.00017	0.73	34.72	701	
13	5.58	560	0.085	8.38	0.047	0.83	1.66	0.909	8.74	3.21	42.07	18.05	92.52	27.19	357.5	87.46	7218	19	63	4.5	0.30	0.00017	0.73	32.51	692	
14	10.5	1665	0.066	30.43	0.072	2.05	4.43	2.7	31.19	11.67	154.2	60.27	293	78.76	1022	226.42	7266	100	222	16.5	0.45	0.00005	0.70	108.23	745	
15	8.93	1091	0.092	19.77	0.098	1.33	2.99	1.67	18.6	7.25	93.94	38.22	184.7	51.12	644.8	147.16	7422	61	144	10.5	0.42	0.00010	0.68	51.05	731	
16	7.6	633.1	0.114	8.95	0.056	0.82	1.77	0.933	9.04	3.41	45.46	20.26	105.4	30.86	422.8	101.41	7226	18	78	5.5	0.23	0.00019	0.71	27.46	717	
17	7.46	1041	0.074	17.04	0.202	3.04	5.33	2.24	21.67	7.29	91.85	38.1	182.8	52.42	674.7	150.21	7397	50	142	10.4	0.35	0.00008	0.64	34.17	716	
18	6.55	711.6	0.135	10.44	0.085	0.78	2.28	0.85	10.08	3.79	54.66	22.7	119.4	34.98	482.4	115.48	7514	20	88	6.2	0.23	0.00020	0.54	23.90	705	
19	7.68	869.9	0.104	13.29	0.083	1.23	2.5	1.23	12.39	4.91	66.66	28.26	148.1	41.5	566.7	133.40	7132	31	106	7.7	0.29	0.00013	0.68	35.07	718	
20	6.9	391.8	0.088	7.59	0.07	0.5	1.18	0.633	5.93	2.35	29.84	12.66	63.02	17.9	244.5	57.28	7765	17	61	4.4	0.28	0.00026	0.73	23.71	709	
21	8.45	729.6	0.114	11.34	0.087	1.1	2.93	1.4	12.62	4.47	57.54	23.15	113.4	32.5	423.4	97.90	6925	29	96	6.9	0.30	0.00019	0.70	27.92	726	
22	6.31	569.5	0.233	7.69	0.102	1.23	2.45	1.53	11.13	3.92	48.25	18.67	90.11	25.03	325.1	73.96	7143	18	58	4.3	0.31	0.00051	0.90	12.23	702	
23	4.42	506.5	0.069	9.24	0.077	1.92	3.33	1.4	10.56	3.43	40.62	15.76	78.98	23.45	319.4	77.24	9126	71	150	11.3	0.48	0.00015	0.72	31.08	674	
24	6.39	804.2	0.148	12.14	0.082	0.87	2.15	0.99	11.31	4.55	61.03	26.29	132.2	36.85	509.5	120.58	7733	30	104	7.5	0.29	0.00021	0.61	27.02	703	
25	6.99	771.6	0.073	11.58	0.193	3.04	5.35	1.69	18.85	5.88	67.89	25.84	118.1	31.47	392.9	83.65	7876	42	92	7.0	0.46	0.00013	0.51	23.92	710	

(La/Yb)_N are chondrite normalized ratio; Ce/Ce* = Ce_N/(La_N × Pr_N)^{1/2}; Eu/Eu* = Eu_N/(Sm_N × Gd_N)^{1/2}; Ti-in-zircon temperature T_{Ti} (°C) = 5080 / (6.01 - logTi_{zircon}) - 273.15 (Watson et al., 2006).

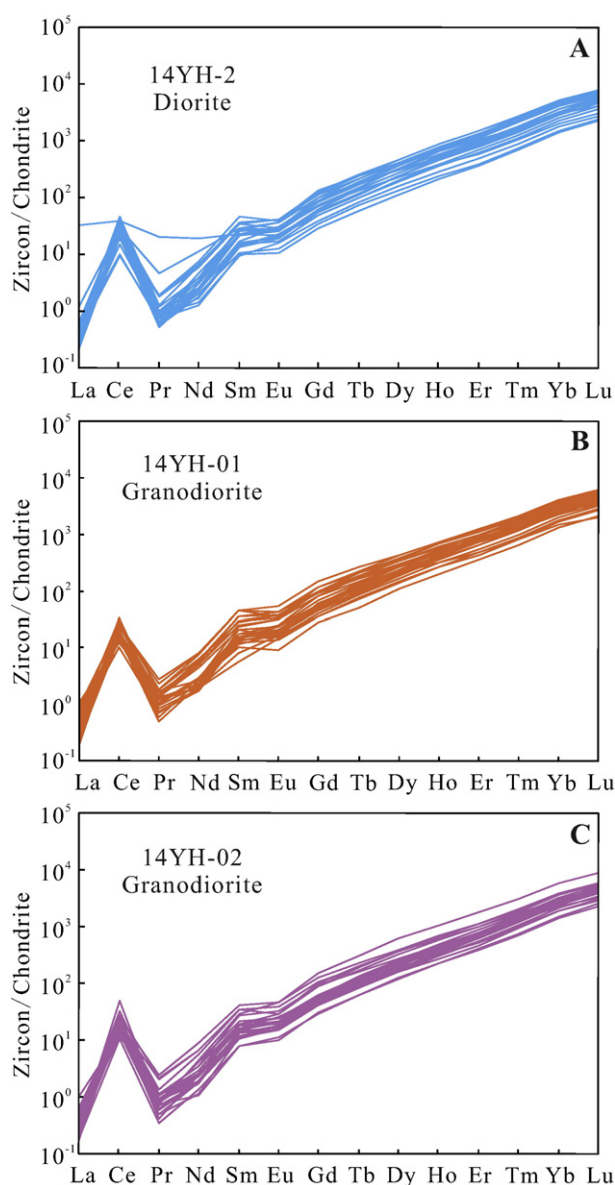


Fig. 6. Chondrite-normalized REE patterns for zircon grains from the Yuhai intrusions. Chondrite values are from Sun and McDonough (1989).

in Re and Os concentrations, which includes weighing error for both spike and sample, uncertainty in spike calibration, and mass spectrometry analytical error.

4. Results

4.1. Zircon U–Pb ages

The Yuhai diorite sample (14YH-2) and granodiorite samples (14YH-01 and 14YH-02) were selected for LA-ICP-MS zircon U–Pb dating, and the analytical data are listed in Table 1. Most of the zircon grains are euhedral-subhedral and show prismatic forms (100–200 μm long) with aspect ratios of 3:2 to 3:1 and exhibit clear oscillatory growth zoning in their CL images (Fig. 5). All of the analyzed zircons have varying U (43–226 ppm) and Th (11–105 ppm) contents, with Th/U ratios ranging from 0.23 to 0.53 (Table 1), which is consistent with a magmatic origin (Hoskin and Schaltegger, 2003). Therefore, the LA-ICP-MS zircon U–Pb dating results are interpreted to represent the timing of zircon

crystallization and thus the age of the magma emplacement. Except for one discordant spot (06), the remaining 24 analyses from the diorite sample (14YH-2) yielded concordant $^{206}\text{Pb}/^{238}\text{U}$ ages varying from 440 to 445 Ma (Fig. 5A), with a weighted mean age of 441.6 ± 2.5 Ma (MSWD = 0.03; $n = 24$). Except for six discordant spots (01, 12, 13, 14, 23, and 24), the remaining 19 analytical spots from the granodiorite sample (14YH-01) had $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 427 to 432 Ma (Fig. 5B), with a weighted mean age of 430.4 ± 2.9 Ma (MSWD = 0.04, $n = 19$). Except for one discordant spot (09), the remaining 24 analytical spots from the granodiorite sample (14YH-02) had $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 423 to 433 Ma (Fig. 5C), with a weighted mean age of 430.3 ± 2.6 Ma (MSWD = 0.09, $n = 24$). Thus, we interpret the weighted mean ages as the emplacement ages of the diorite and granodiorite at Yuhai.

4.2. Zircon trace elements

Trace element analyses carried out on zircons from sample 14YH-2 yielded relatively low U (43–226 ppm) and Th (11–105 ppm) contents, with corresponding Th/U ratios of 0.25–0.53 (Table 2). They displayed pronounced LREE depletion with $(\text{La}/\text{Yb})_{\text{N}} = 0.00006\text{--}0.01422$, positive Ce anomalies with $\text{Ce}/\text{Ce}^* = 1.51\text{--}76.84$ and negative Eu anomalies with $\text{Eu}/\text{Eu}^* = 0.50\text{--}0.83$ (Fig. 6A), similar to those of typical magmatically crystallized zircons (Schaltegger et al., 1999; Hoskin and Ireland, 2000; Hoskin and Schaltegger, 2003; Whitehouse and Platt, 2003). The trace element analyses on zircons from samples 14YH-01 and 14YH-02 had similar U (47–222 ppm) and Th (13–100 ppm) contents and Th/U ratios (0.23–0.51) (Table 2). In addition, these samples had similar chondrite normalized REE patterns with significant HREE enrichments ($(\text{La}/\text{Yb})_{\text{N}} = 0.00005\text{--}0.00080$), and showed strong positive Ce anomalies ($\text{Ce}/\text{Ce}^* = 9.14\text{--}108.23$) and negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.44\text{--}1.04$) (Fig. 6B, C). The calculated results of the Ti-in-zircon thermometer can be used to determine the genetic setting of zircons (Fu et al., 2009). The calculated Ti-in-zircon thermometer varied from 680 to 750 $^{\circ}\text{C}$ (avg. 713 $^{\circ}\text{C}$, $n = 25$) in the diorite and 680 to 789 $^{\circ}\text{C}$ (avg. 713 $^{\circ}\text{C}$, $n = 25$) and 674 to 745 $^{\circ}\text{C}$ (avg. 708 $^{\circ}\text{C}$, $n = 25$) in the granodiorite (Table 2). Magmatic zircons crystallize from ore-forming fluids at temperatures higher than 600 $^{\circ}\text{C}$ (Fu et al., 2009; Wan et al., 2012). Therefore, the high formation temperatures and Th/U values of the zircons from the Yuhai deposit can be taken as evidence for their crystallization from magmas, and their Hf isotope compositions can be employed to evaluate their source characteristics.

4.3. Re–Os isotopic ages

The Re–Os isotopic data for four molybdenite samples from the Yuhai porphyry Cu–Mo deposit are listed in Table 3 and are plotted in an isochron diagram in Fig. 7. The concentrations of ^{187}Re and ^{187}Os ranged from 13.5 to 52.2 $\mu\text{g}/\text{g}$ and from 79.9 to 307.9 ng/g, respectively. Four samples yielded model ages ranging from 357.9 ± 4.6 to 353.0 ± 5.0 Ma and a well-constrained $^{187}\text{Re}\text{--}^{187}\text{Os}$ isochron age of 351.7 ± 2.9 Ma, with MSWD = 1.5 and an initial ^{187}Os of 1.1 ± 0.8 ng/g (Fig. 7A). The data also produced a weighted average age of 355.7 ± 2.4 Ma (MSWD = 0.69) (Fig. 7B). These two ages are concordant within their error limits and indicate that the Yuhai deposit was mineralized in the Carboniferous.

4.4. Whole-rock geochemistry

The representative whole-rock geochemical data for the Yuhai intrusive samples are presented in Table 4, and they plot in the diorite and granodiorite fields on the $\text{Na}_2\text{O} + \text{K}_2\text{O}$ vs. SiO_2 diagram (Fig. 8A; Le Maitre, 2002). The diorite is characterized by high SiO_2 (58.30–62.86 wt.%), Al_2O_3 (15.24–17.36 wt.%) and MgO (1.95–4.80 wt.%) and low $\text{K}_2\text{O} + \text{Na}_2\text{O}$ (3.88–6.32 wt.%), TiO_2 (0.38–0.54 wt.%), P_2O_5 (0.18–0.28 wt.%) and MnO (0.06–0.19 wt.%), which belong to the low-K

Table 3
Molybdenite Re–Os isotopic data for the Yuhai porphyry Cu–Mo deposit.

Sample no.	Weight (g)	Ores type	Occurrence	$\text{Re}/\mu\text{g}\cdot\text{g}^{-1}$		$\text{Os}/\text{ng}\cdot\text{g}^{-1}$		$^{187}\text{Re}/\mu\text{g}\cdot\text{g}^{-1}$		$^{187}\text{Os}/\text{ng}\cdot\text{g}^{-1}$		Model age (Ma)	
				Measured	2σ	Measured	2σ	Measured	2σ	Measured	2σ	Measured	2σ
14YH-13	0.00976	Mo mineralized diorite	Dissemination	83.1	0.69	0.4687	0.0451	52.2	0.43	307.9	1.9	353.0	5.0
14YH-14	0.01048	Mo mineralized granodiorite	Dissemination	22.1	0.13	0.1756	0.0333	13.9	0.08	83.0	0.48	357.9	4.6
14YH-15	0.01013	Ccp-Mo-Qz veinlet	Veinlet	21.4	0.16	0.141	0.0393	13.5	0.1	79.9	0.52	355.6	5.0
14YH-10	0.00525	Ccp-Mo-Qz veinlet	Veinlet	23.0	0.18	0.1945	0.0475	14.5	0.11	85.9	0.5	355.8	4.9

tholeiite series (Fig. 8B). The granodiorite exhibited slightly different major element compositions, having $\text{SiO}_2 = 62.87\text{--}64.32$ wt.%, $\text{Al}_2\text{O}_3 = 17.05\text{--}17.39$ wt.%, $\text{MgO} = 1.84\text{--}2.55$ wt.% and $\text{Mg}^\# = 40 - 49[100 \times \text{molecular Mg}^{2+} / (\text{Mg}^{2+} + \text{Fe}^{2+})]$; Fig. 8C). These rocks are characterized by low K_2O (0.41–1.33 wt.%), and $\text{TFe}_2\text{O}_3/\text{MgO}$ (2.05–3.03), which suggests that they are low-K tholeiite series rocks (Fig. 8B). In the chemical variation diagrams of selected major oxides (Fig. 9), the TFe_2O_3 , TiO_2 , MnO, MgO and Na_2O contents of all of the intrusive samples correlated negatively with the SiO_2 contents, which suggests possible fractional crystallization during the intrusive process.

In the chondrite-normalized rare earth element (REE) diagram (Fig. 10A; Boynton, 1984), the diorite samples are moderately fractionated ($(\text{La}/\text{Yb})_N = 4.19\text{--}7.64$), with light rare earth element (LREE) enrichment and heavy rare earth element (HREE) depletion in the absence of clear Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.92\text{--}1.27$). Moreover, the granodiorite samples had slightly different REE patterns ($(\text{La}/\text{Yb})_N = 6.40\text{--}19.64$), and the values of the positive Eu anomaly ranged from 1.03 to 1.36 (Fig. 10C). In the primitive mantle-normalized trace element spider diagram (Fig. 10B, D; Sun and McDonough, 1989), both of the diorite and granodiorite samples show an enrichment in U, Pb and large ion lithophile elements (LILEs) such as K, Ba and Sr and a depletion in high field strength elements (HFSEs) such as Th, Nb, Ta and Ti.

4.5. Zircon Hf isotope systematics

In situ Hf isotopic data for zircons from three samples of 14YH-2 (diorite), 14YH-01 and 14YH-02 (granodiorite) are shown in Fig. 11, and the zircon Hf isotopic data and calculation results are presented in Table 5. The magmatic zircons from diorite (441.6 ± 2.5 Ma) exhibited variable Hf isotopic compositions, with $^{176}\text{Hf}/^{177}\text{Hf}$ ratios ranging from 0.282754 to 0.283035. The positive $\epsilon_{\text{Hf}}(t)$ values and Hf isotopic crustal model ages (T_{DM}^{C}) ranged from $+8.7$ to $+18.6$ and from 234 to 872 Ma, respectively (Table 5; Fig. 11). The magmatic zircons from granodiorite (430.4 ± 2.9 Ma) had $^{176}\text{Hf}/^{177}\text{Hf}$ ratios varying from 0.282869 to 0.283028, with positive $\epsilon_{\text{Hf}}(t)$ values and corresponding T_{DM}^{C} ages

ranging from $+12.6$ to $+19.6$ and from 213 to 612 Ma, respectively (Table 5; Fig. 11). The magmatic zircons from granodiorite (430.3 ± 2.6 Ma) exhibited $^{176}\text{Hf}/^{177}\text{Hf}$ ratios varying from 0.282871 to 0.283052, with positive $\epsilon_{\text{Hf}}(t)$ values and corresponding T_{DM}^{C} ages ranging from $+12.6$ to $+18.9$ and from 209 to 611 Ma, respectively (Table 5; Fig. 11).

5. Discussion

5.1. Timing of magmatism and mineralization

According to previous studies, widespread magmatism occurred in the eastern Tianshan orogenic belt (Mao et al., 2005; Wang et al., 2006; Tang et al., 2007; Zhou et al., 2010; Wang et al., 2015b, c), and the abundant intrusive rocks, including granodiorite, tonalite, quartz porphyry, granite porphyry, biotite granite, monzogranite, syenogranite, A-type granite and alkali-feldspar granite (Liu et al., 2007; Qin et al., 2011; Han et al., 2014; Zhang et al., 2015a, b), are mainly divided into two magmatic stages: Paleozoic and Mesozoic. Magmatic activity during these two episodes showed a close temporal and spatial relationship with Cu (\pm Ni), Mo, Au, Fe and Ag mineral systems, whereas the Late Paleozoic is considered to have been the most important magmatic–metallogenic episode in eastern Tianshan (Mao et al., 2005; Pirajno et al., 2011; Wang et al., 2015b, c). However, numerous zircon U–Pb dates and Rb–Sr dates on host rocks have revealed some Early Paleozoic magmatic events in the Tianshan orogen (Zhang et al., 2008; Shu et al., 2004). These magmatic rocks mainly include the Mishigou gabbro (468 Ma; Shu et al., 1999), monzogranite (470 ± 3.0 Ma; Gu et al., 1999) and granite (435 Ma; Hopson et al., 1989) in Central Tianshan, and the Sanchakou granodiorite (443 ± 2.9 Ma; Wang et al. 2015f), Xingxingxia granodiorite (424.9 ± 5.8 Ma; Lei et al., 2011) and Weiya granulite (432 ± 1 Ma; Shu et al., 2004) in eastern Tianshan, which represent a significant Early Paleozoic magmatic hydrothermal event. Moreover, the LA-ICP-MS zircon U–Pb dating results in this study indicate that the Yuhai diorite was emplaced at 441.2 ± 2.5 Ma, while the granodiorite formed at

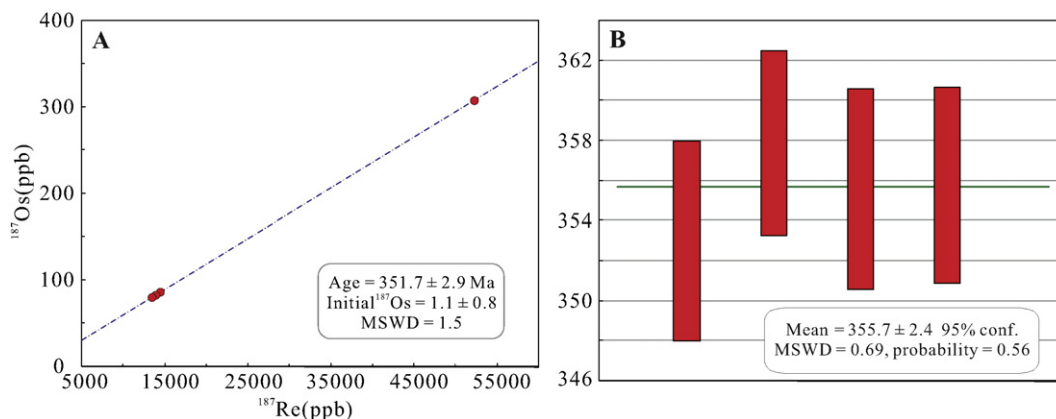


Fig. 7. Re–Os isochron diagram and weighted average model age diagram for four molybdenite samples in the Yuhai porphyry Cu–Mo deposit.

Table 4

Whole-rock geochemical data of the Yuhai diorite and granodiorite in eastern Tianshan (Major elements: wt.%; Trace elements: ppm).

Sample no.	14YH-1	14YH-8	14YH-3	14YH-5	14YH-6	14YH-7	14YH-4	YH-1	YH-2	YH-4	YH-6	YH-7	YH-9
Reference	This study	This study	This study	This study	This study	This study	This study	Zang (2014)	Zang (2014)	Zang (2014)	Zang (2014)	Zang (2014)	Zang (2014)
Rock type	Granodiorite	Granodiorite	Granodiorite	Granodiorite	Granodiorite	Granodiorite	Diorite	Diorite	Diorite	Diorite	Diorite	Diorite	Diorite
SiO ₂	63.17	62.87	63.25	63.33	64.32	64.29	61.30	60.72	58.30	62.27	62.57	61.10	62.86
TiO ₂	0.39	0.39	0.41	0.40	0.36	0.36	0.40	0.54	0.53	0.42	0.42	0.38	0.39
Al ₂ O ₃	17.21	17.39	17.23	17.36	17.17	17.05	16.91	17.36	17.35	16.56	16.18	15.24	16.90
TFe ₂ O ₃	5.22	5.57	5.84	5.65	5.22	5.35	5.49	6.39	7.96	6.94	6.76	7.58	5.34
MnO	0.06	0.06	0.10	0.09	0.08	0.08	0.06	0.13	0.16	0.19	0.18	0.14	0.14
MgO	2.55	1.91	1.93	1.88	1.84	1.94	2.63	2.64	2.70	2.43	2.86	4.80	1.95
CaO	4.18	5.67	5.98	6.00	5.79	5.62	4.48	4.70	5.29	5.02	4.39	4.19	5.03
Na ₂ O	4.18	4.13	3.85	4.05	3.80	3.52	3.99	5.89	3.68	3.53	3.14	3.53	4.44
K ₂ O	1.33	0.41	0.66	0.58	0.42	0.46	0.63	0.43	0.52	0.60	0.74	0.44	1.31
P ₂ O ₅	0.21	0.25	0.21	0.20	0.20	0.20	0.23	0.28	0.26	0.21	0.20	0.18	0.20
LOI	1.49	1.32	0.54	0.44	0.79	1.11	3.37	1.11	3.29	2.10	2.88	2.71	1.50
Total	99.99	99.98	99.99	99.98	99.99	99.98	99.50	100.19	100.04	100.27	100.32	100.29	100.06
Na ₂ O + K ₂ O	5.51	4.54	4.51	4.63	4.22	3.98	4.62	6.32	4.20	4.13	3.88	3.97	5.75
Mg [#]	49	41	40	40	41	42	49	45	40	41	46	56	42
A/CNK	1.08	0.99	0.96	0.95	1.00	1.03	1.10	0.93	1.07	1.06	1.16	1.10	0.94
A/NK	2.07	2.40	2.45	2.38	2.56	2.71	2.33	1.71	2.62	2.56	2.71	2.42	1.94
FeO	2.47	2.92	3.36	2.81	3.18	2.52	1.91	2.94	2.66	3.14	3.4	3.6	2.42
TFe ₂ O ₃ /MgO	2.05	2.92	3.03	3.01	2.84	2.76	2.09	2.42	2.95	2.86	2.36	1.58	2.74
Li	2.06	3.77	3.48	2.54	5.4	6.16	3.98						
Be	0.831	0.964	0.783	0.929	0.638	0.58	0.853						
Sc	10.9	9.52	10.5	9.88	9.9	8.75	13.3						
V	102	84	87	75.5	91.3	74	114	106	120	104	98.4	92.7	71.7
Cr	60.9	97.5	104	71	101	75.4	72.5	37.1	21.3	16.5	82.6	133	9.8
Co	4.07	11.5	13	10.4	8	7.69	20	16.5	25.6	14.8	13.8	34.9	10.1
Ni	4.95	5.44	6.1	4.93	5.45	4.86	5.4						
Cu	87.3	116	343	19.8	204	325	210	62.4	910	240	154	594	14.2
Zn	42.1	37.8	63.8	57.9	41.4	42.2	46.1						
Ga	16.2	18.5	17.8	17.2	17.7	16.3	18.4						
Rb	30.5	5.92	10.1	8.69	6.34	5.83	11.3						
Sr	609	913	786	770	866	781	772	790	816	779	709	607	759
Y	12.7	13.9	14.6	13.5	11.5	10.6	17.4	15.5	10.3	15.2	14.2	14.6	12.8
Zr	71.2	84.2	79.4	76.3	73.4	65.4	78.7	82.6	73.1	61.5	65.6	63.5	70.9
Nb	2.73	7.57	2.18	1.99	2.44	1.87	2.83	3.72	2.78	2.52	2.61	2.33	2.31
Cs	0.24	0.096	0.152	0.155	0.083	0.092	0.198	0.12	0.13	0.15	0.16	0.15	0.3
Ba	457	430	842	637	416	321	336	218	416	498	326	375	754
La	20.1	43.8	18	16.1	11.6	15	14.2	19.8	8.48	16.5	16.3	16	14.9
Ce	35.5	76.3	34.2	31.1	21.3	27.9	27.5	41.7	19.4	35.1	33.6	32.9	32.3
Pr	4.37	8.43	4.4	4.1	2.92	3.51	3.76	5.52	2.52	4.55	4.32	4.16	4.1
Nd	17.8	33.7	18.6	17.8	13.1	14.9	17.3	23.2	10.4	18.6	17.8	17.2	16.7
Sm	3.12	5.35	3.52	3.36	2.57	2.72	3.74	4.79	2.47	3.85	3.6	3.61	3.5
Eu	1.01	1.66	1.24	1.11	1.08	1.05	1.15	1.3	0.99	1.22	1.06	1.13	1.15
Gd	2.75	4.13	2.77	2.53	2.28	2.35	3.14	3.89	2.3	3.42	3.18	3.17	3
Tb	0.498	0.577	0.481	0.481	0.336	0.419	0.554	0.55	0.33	0.5	0.47	0.46	0.43
Dy	2.44	2.8	2.55	2.86	1.91	2.03	3.25	3.06	1.89	2.9	2.74	2.76	2.59
Ho	0.486	0.452	0.49	0.441	0.378	0.371	0.552	0.6	0.39	0.61	0.57	0.57	0.53
Er	1.33	1.33	1.34	1.34	1.23	1.21	1.84	1.72	1.17	1.76	1.7	1.65	1.52
Tm	0.253	0.238	0.235	0.291	0.213	0.181	0.318	0.27	0.2	0.28	0.28	0.28	0.24
Yb	1.6	1.6	1.38	1.53	1.3	1.26	1.93	1.86	1.45	1.98	1.89	1.9	1.7
Lu	0.223	0.25	0.258	0.295	0.258	0.208	0.344	0.28	0.24	0.31	0.3	0.3	0.27
Hf	2.25	2.53	2.57	2.24	2.27	2.13	2.35	2.49	2.3	1.95	2.1	2.02	2.29
Ta	0.238	0.165	0.135	0.118	0.122	0.129	0.196	0.43	0.3	0.26	0.27	0.25	0.27
Pb	7.4	6.26	6	5.18	4.73	4.79	3.87	3.73	11.3	6.85	5.25	5.54	13
Th	1.89	3.61	1.23	1.17	1.56	1.46	1.8	2.25	1.79	1.58	1.6	1.44	1.27
U	1.46	5.12	0.658	0.58	0.886	0.871	1.23	1.04	0.94	0.72	0.69	0.72	0.63
(La/Yb) _N	9.01	19.64	9.36	7.55	6.40	8.54	5.28	7.64	4.19	5.98	6.19	6.04	6.29
Eu/Eu*	1.05	1.08	1.21	1.16	1.36	1.27	1.03	0.92	1.27	1.03	0.96	1.02	1.08
Sr/Y	47.95	65.68	53.84	57.04	75.30	73.68	44.37	50.97	79.22	51.25	49.93	41.58	59.30
La/Yb	12.56	27.38	13.04	10.52	8.92	11.90	7.36	10.65	5.85	8.33	8.62	8.42	8.76
Zr + Nb + Ce + Y	122.13	181.97	130.38	122.89	108.64	105.77	126.43	143.52	105.58	114.32	116.01	113.33	118.31
10,000Ga/Al	1.78	2.01	1.95	1.87	1.95	2.06							

LOI = loss on ignition. A/CNK = molecular Al₂O₃ / (CaO + Na₂O + K₂O); A/NK = molecular Al₂O₃ / (Na₂O + K₂O). Mg[#] = 100 × molecular Mg²⁺ / (Mg²⁺ + Fe²⁺), calculated by assuming TFeO = 0.9 × TFe₂O₃. Eu/Eu* = Eu_N / (Sm_N × Gd_N)^{1/2}, the subscript of N means normalized to chondrite (Sun and McDonough, 1989).

430.4 ± 2.9 Ma to 430.3 ± 2.6 Ma. The geochronology data confirms that they were intruded in the Early Silurian. These data and previous geochronological data demonstrate that the Early Paleozoic magmatic activity was also developed in the eastern Tianshan orogenic belt (Fig. 1C).

In addition, the internally concordant Re–Os model ages of four molybdenite samples from the Yuhai deposit implies that the Re–Os system had been closed, and the molybdenite Re–Os ages can therefore represent its depositional age. Therefore, the weighted mean model

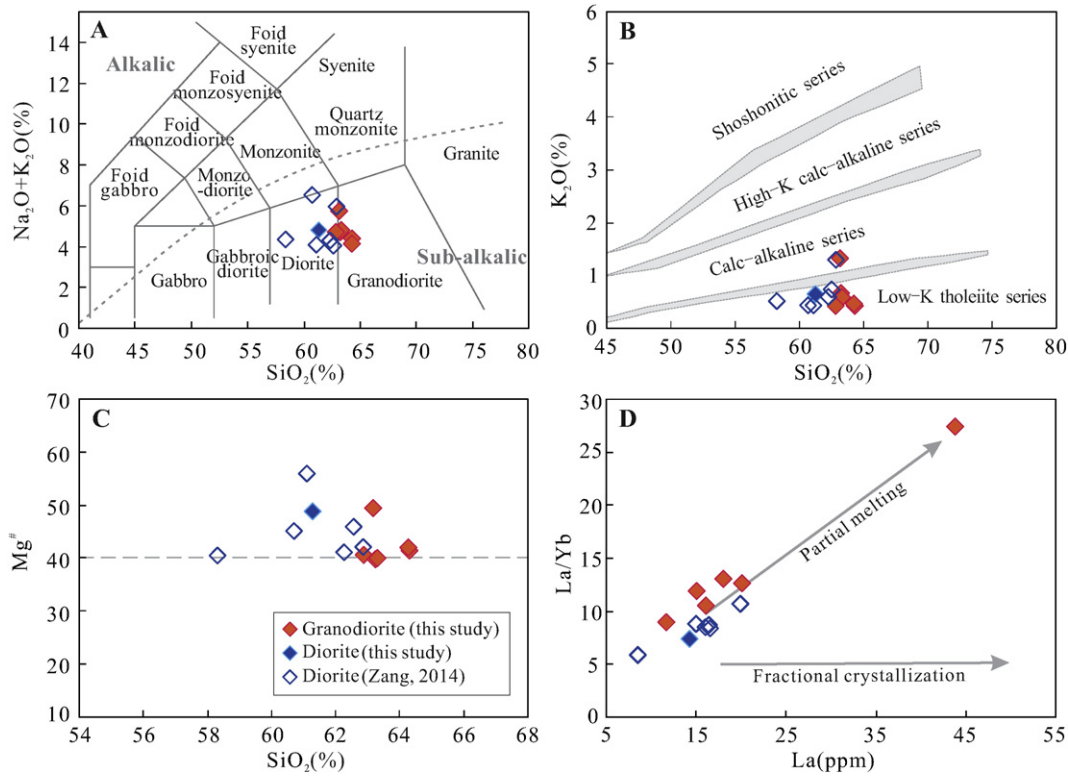


Fig. 8. Classification and diagrams of the Yuhai intrusions. (A) $\text{Na}_2\text{O} + \text{K}_2\text{O}$ vs. SiO_2 diagram (Le Maitre, 2002); (B) K_2O vs. SiO_2 diagram (Rollinson, 1993); (C) $\text{Mg}^\#$ vs. SiO_2 diagram; (D) La/Sm vs. La diagram.

age (355.7 ± 2.4 Ma) of the four analyses precisely dates the hydrothermal deposition of molybdenite at Yuhai. Combined with the new LA-ICP-MS zircon U–Pb ages presented herein ($441\text{--}430$ Ma), the Re–Os isotopic ages (355.7 ± 2.4 Ma) obtained in this study indicate that the Cu mineralization in the Yuhai area occurred later than the intrusive rock emplacement there. Based on the crosscutting relationships, the molybdenite-bearing veinlets associated with phyllic alteration are present in the diorite and granodiorite. They also indicate that the Re–Os ages of the molybdenite should be later than the intrusion age of the diorite and granodiorite and may be the same as the late ore-forming age at Yuhai. Such a discrepancy has been interpreted to be related to the involvement of multiple hydrothermal events. Zang (2014) indicated that certain Carboniferous intrusions developed in the southern Yuhai area. This is comparable to the situation of the Tuwu–Yandong porphyry Cu deposits located in eastern Tianshan. For example, a range of zircon U–Pb ages from 361.8 ± 7.8 to 332.2 ± 2.3 Ma for plagiogranite porphyry (Rui et al., 2002; Wang et al., 2015b, c), Re–Os isotopic ages of $189\text{--}195$ Ma for Cu-mineralized plagiogranite porphyry (Gao et al., 2015), K–Ar age of 341.2 ± 4.9 Ma (Qin et al., 2002) and Re–Os isotopic ages of $323\text{--}343$ Ma for molybdenite (Rui et al., 2002; Zhang et al., 2008) have been obtained in the Tuwu–Yandong deposits. Therefore, multiple hydrothermal events may have been important for the formation of the Yuhai porphyry Cu deposits.

5.2. Petrogenesis and source of the magma

The petrochemical signatures of intrusive rocks record important information on magma sources (Barbarin, 1999; Chen et al., 2007), magmatic processes (Sylvester, 1998; Deng and Wang, 2015; Deng et al., 2015b; Zhu et al., 2011) and tectonic settings (Sillitoe, 1972, 2010; Wu et al., 2007; Wang et al., 2015; Zhang et al., 2016); therefore, it is important to have a clear understanding of the petrogenetic history of

the Yuhai intrusions. The Yuhai intrusions mainly consist of diorite and granodiorite, with SiO_2 contents ranging from 58.30 to 64.32 wt.%, Al_2O_3 contents ranging from 15.24 to 17.39 wt.% and MgO contents ranging from 1.84 to 4.80 wt.% (Table 4). They have relatively high Sr concentrations (607–913 ppm) and low Y (10.3–17.4 ppm) and HREE concentrations ($\text{Yb} = 1.26\text{--}1.98$ ppm), with geochemical compositions similar to those of modern adakites (Defant et al., 1991). However, compared to adakites, the Yuhai intrusions contain lightly lower SiO_2 and higher MgO contents (Fig. 8C). They also show lower abundances of LREE and LILE (Fig. 10) and variable Y and Yb_N values (Table 4) relative to adakites (Defant et al., 1991) and plot in a transitional adakite to typical arc field in the Sr/Y vs. Y and $(\text{La}/\text{Yb})_N$ vs. Yb_N diagrams (Fig. 12A, B; Defant and Drummond, 1990).

The Yuhai dioritic and granodioritic intrusions have similar geochemical characteristics that indicate a relatively uniform and integrated magmatic origin beneath eastern Tianshan. In detail, they are characterized by a strong LREE enrichment, moderate HREE depletion and slightly positive Eu anomalies that reflect clear subduction signatures. They also have less variable La contents but variation in the La/Yb ratios, which suggest that the partial melting process was dominant in their petrogenesis (Fig. 8D). In addition, the Yuhai intrusions show pronounced depletions of Nb, Ta and Ti and enrichments of K, Rb and Pb (Fig. 10B), similar to those of most modern subduction-related plutonic rocks (Wood et al., 1979; Briquieu et al., 1984; Shen et al., 2014) formed by the partial melting of subducted oceanic slabs.

Experimental studies have shown that $\text{Mg}^\#$ is a useful criterion for distinguishing melts purely derived from the crust from those involved in the mantle. Melts from the basaltic lower crust are characterized by a low $\text{Mg}^\#$ less than 40 regardless of melting degree, whereas those with $\text{Mg}^\#$ greater than 40 can only be obtained when a mantle component is involved (Rapp and Watson, 1995; Rapp et al., 1999; Guan et al., 2011; Zhu et al., 2009, 2013). All of the Yuhai diorite and granodiorite rocks

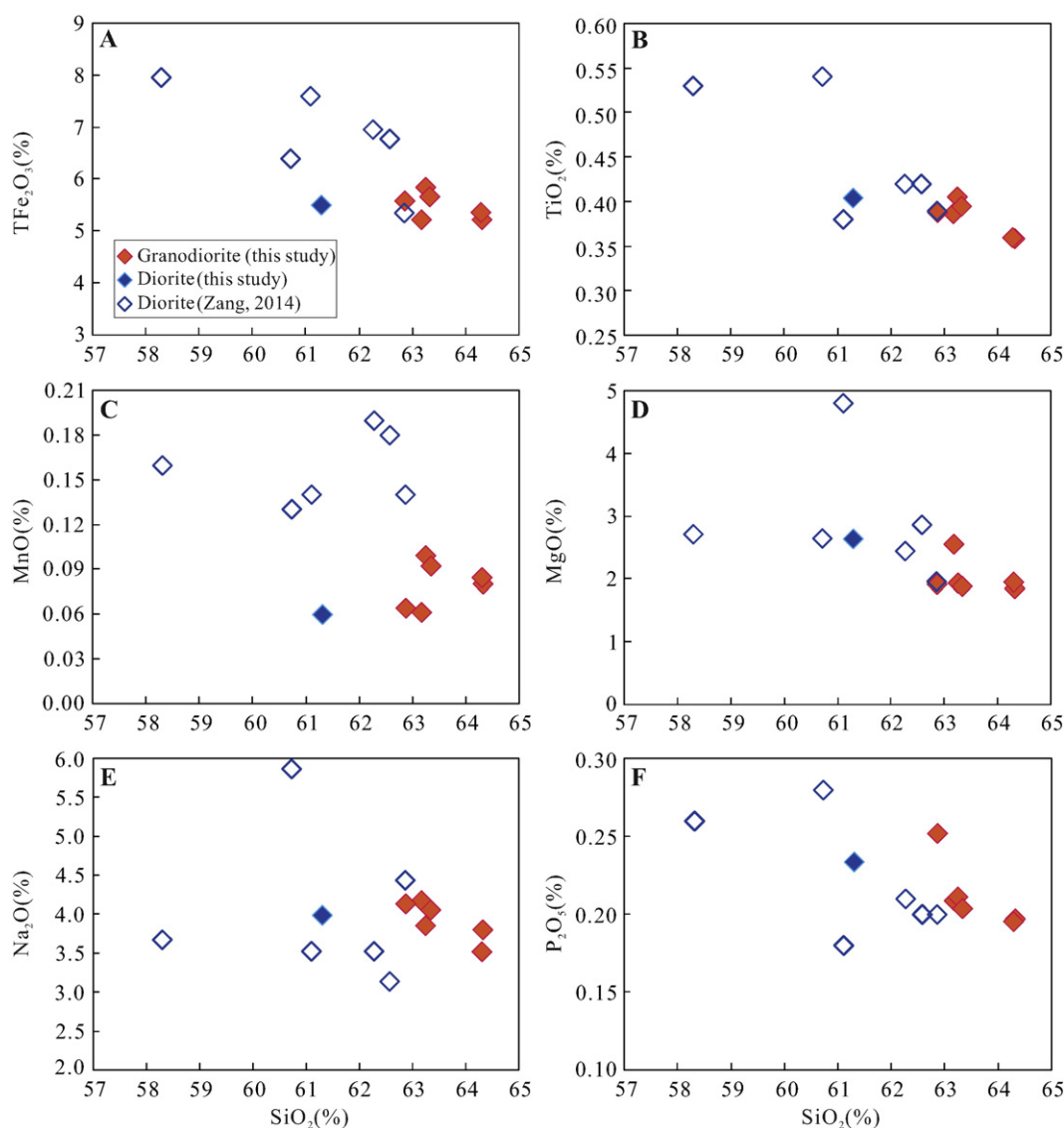


Fig. 9. Harker diagram of intrusions in the Yuhai porphyry Cu–Mo deposit.

show features of high MgO contents (1.84–4.80 wt.%) and $Mg^\#$ values (40–56) (Fig. 8C), which indicate the involvement of mantle components.

These results are supported by the zircon Hf isotopic data (Table 5). The Hf isotopic compositions of the intrusions from the Yuhai area are characterized by positive $\epsilon_{Hf}(t)$ values, which range from +8.7 to +18.6 of magmatic zircons from a diorite sample (14YH-1) and from +12.6 to +19.6 of zircons from granodiorite samples (14YH-01 and 14YH-02) (Table 5; Fig. 11A). They also show young Hf model ages (T_{DM}^C), which are between 234 and 872 Ma (diorite) and between 209 and 612 Ma (granodiorite) (Table 5; Fig. 11B). In the $\epsilon_{Hf}(t)$ vs. U–Pb age diagram (Fig. 11C), zircons from these samples show a spread of $\epsilon_{Hf}(t)$ values near the depleted mantle evolution line, which indicates that they were most likely derived from a depleted mantle source. Given the normal island arc affinities and inhomogeneous $\epsilon_{Hf}(t)$ values (greater than 6.3ϵ units) recorded in the Yuhai diorite and granodiorite rocks, it is suggested that the melt of those intrusions could be a product of the partial melting of mantle components that were previously metasomatized by slab melts.

Considering the entire dataset, it is proposed that the Yuhai intrusions share similar petrochemical signatures to those formed in an

island arc, namely the Dananhu–Tousuquan arc. The primary magmas for the diorite (~442 Ma) and granodiorite (~430 Ma) intrusions were most likely derived from the partial melting of the subduction-modified mantle components.

5.3. Implications for the geodynamic setting and Cu–Mo mineralization

The intrusive rocks analyzed in this study and in previous research were found to have transitional tholeiite to calc-alkaline affinities, enriched in LREEs and LILEs (e.g., K, Ba, Pb and Sr) and depleted in HFSEs (e.g., Th, Nb, Ta, and Ti), indicating a magma that formed in a relatively immature island arc setting (Miyashiro, 1974; Liégeois et al., 1998). The granodioritic samples plot within the volcanic arc field in the Rb vs. (Ta + Yb) tectonic discrimination diagram (Fig. 13A; Pearce et al., 1984) and all of the intrusive samples fall between the EMORB and OIB areas in the Th/Yb vs. Nb/Yb diagram (Fig. 13B; Pearce and Peate, 1995; Sayit and Goncuoglu, 2009), which are characteristics of island arc igneous rocks emplaced during the Silurian subduction of an oceanic slab. Their isotopic compositions ($\epsilon_{Hf}(t) = +8.7$ to +19.6) match that of a depleted mantle source. Thus, we suggest that the Yuhai intrusions were formed in an island arc setting.

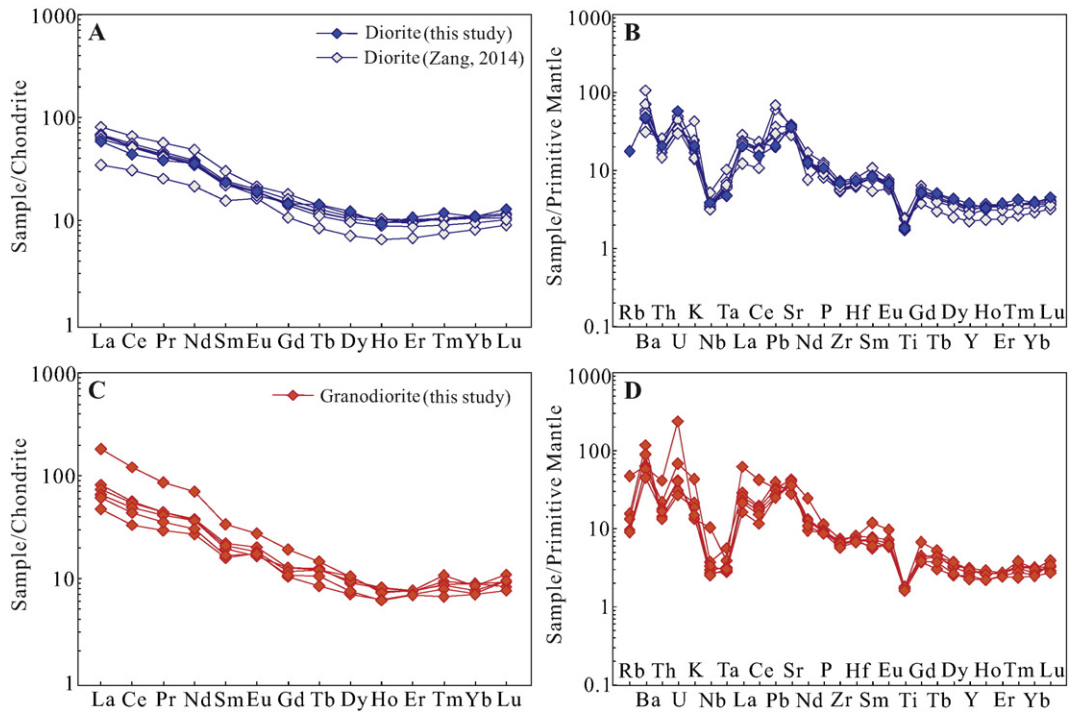


Fig. 10. Chondrite-normalized REE (A, C) and primitive mantle-normalized trace element abundance spider diagram (B, D) for the Yuhai intrusions. Normalized data are from Boynton (1984) and Sun and McDonough (1989).

Most porphyry Cu deposits reported throughout the world occurred in magmatic arcs above subduction zones (Cooke et al., 2005; Seedorff et al., 2005; Sillitoe, 2010) and are associated with calc-alkaline magmas (Richards, 2003; Hou et al., 2013). Those deposits include the El Teniente, Río Blanco–Los Bronces and Los Pelambres porphyry Cu deposits in central Chile (Reich et al., 2003; Jiang et al., 2010), the Chuquicamata porphyry Cu deposit in northern Chile (Barra et al., 2013), the Arynnuur porphyry Mo deposit in East Mongolia (Liu et al., 2010) and the Tuwu–Yandong–Linglong–Chihu porphyry Cu deposits in North Xinjiang (Zhang et al., 2008; Wang et al., 2014; Xiao et al., 2015b). Therefore, magmatic arcs above subduction zones have been shown to be favorable tectonic settings for the generation of porphyry Cu deposits (Defant et al., 2002; Reich et al., 2003; Sun et al., 2010; Yang et al., 2012, 2014).

As reported in previous studies, widespread Paleozoic–Mesozoic granitoids and volcanic rocks were emplaced in eastern Tianshan orogenic belt (Fig. 1C; Wang et al., 2006; Chen et al., 2012b, 2014) during a complex tectonic–magmatic evolution that included subduction and accretion followed by the collision between the Siberian and Tarim Cratons (Han et al., 2006; Xiao et al., 2010, 2013; Santosh et al., 2011). Recently, a large number of Paleozoic (443–322 Ma) rocks with arc affinity have been reported in the Dananhu–Tousuquan arc belt, including Sanchakou granodiorites (443 ± 2.9 Ma; Wang et al., 2015f), Yuhai diorites and granodiorites (441.6 ± 2.5 Ma, and 430.4 ± 2.9 Ma and 430.3 ± 2.6 Ma, respectively; this study), Dananhu granodiorites and monzogranites (357.3 ± 6.2 and 383 ± 9 Ma, respectively; Song et al., 2002), Yandong diorite porphyries and tonalites (340 ± 3 and 335 ± 3.7 Ma, respectively; Shen et al., 2014; Wang et al., 2015b), Tuwu tonalites (332.3 ± 5.9 Ma; Wang et al., 2015c) and Chihu tonalites (320.2 ± 2.4 Ma; Zhang et al., 2015b), which are interpreted to be related to subduction tectonic settings. This indicates that the subduction of the ancient Tianshan Ocean most likely began in the Silurian (Xiao et al., 2013; Wang et al., 2015f; Zhao et al., 2015). On the basis of previous studies, the geodynamics of the eastern Tianshan orogenic belt can be summarized in two stages: the double-sided subduction of the ancient Tianshan oceanic plate, which was probably initiated during the Silurian to Carboniferous and led to the formation of the Dananhu–Tousuquan

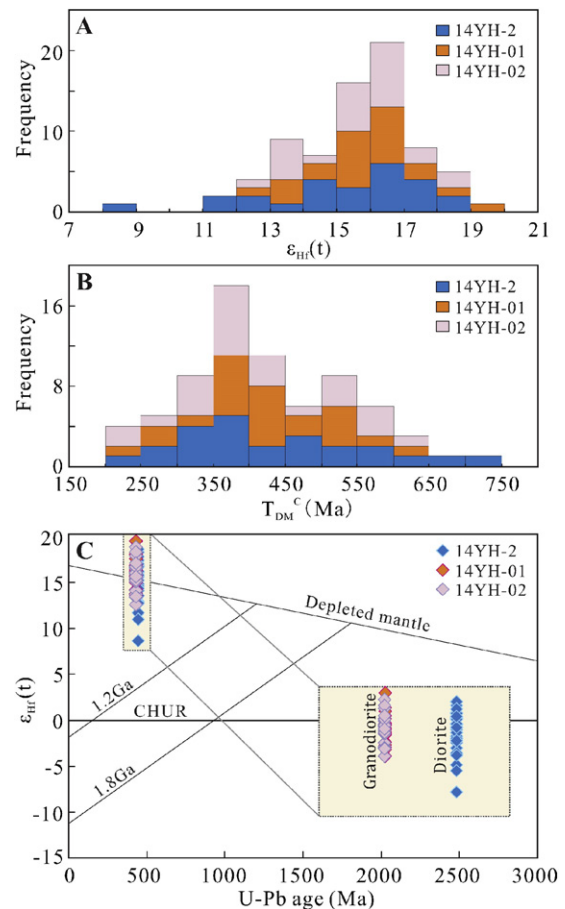


Fig. 11. (A) Histogram of zircon $\epsilon_{\text{Hf}}(t)$ values; (B) Histogram of zircon Hf-isotope crust model age (T_{DM}^c); (C) Correlation diagrams of zircon Hf isotopes versus U–Pb ages of the Yuhai intrusions. The concentration of Hf in N-type MORB from Sun and McDonough (1989) is used to represent the composition of melt derived from depleted mantle.

Table 5 (continued)

Spot	Age/Ma	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	$\pm 2\sigma$	$^{176}\text{Hf}/^{177}\text{Hf}(t)$	$^{176}\text{Hf}/^{177}\text{Hf}$ CHUR(t)	$\varepsilon_{\text{Hf}}(0)$	$\varepsilon_{\text{Hf}}(t)$	$\pm 2\sigma$	T_{DM}/Ma	$T_{\text{DM}}^{\text{C}}/\text{Ma}$	$f_{\text{Lu/Hf}}$
14YH-02 22	431	0.016909	0.000880	0.282953	0.000028	0.282946	0.282504	6.4	15.6	1.0	423	417	-0.97
14YH-02 23	431	0.026938	0.001419	0.282896	0.000032	0.282884	0.282504	4.4	13.5	1.1	511	557	-0.96
14YH-02 24	429	0.035169	0.001843	0.283036	0.000031	0.283021	0.282505	9.3	18.3	1.1	313	247	-0.94
14YH-02 25	433	0.020494	0.000984	0.282993	0.000029	0.282985	0.282503	7.8	17.1	1.0	366	327	-0.97

$$\varepsilon_{\text{Hf}}(t) = 10,000 \times \left(\left[\frac{(^{176}\text{Hf}/^{177}\text{Hf})_{\text{S}} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{S}} \times (e^{\lambda t} - 1)}{[(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR}}]_0 - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} \times (e^{\lambda t} - 1)} \right] - 1 \right),$$

$$T_{\text{DM}} = 1/\lambda \times \ln \left\{ 1 + \left[\frac{(^{176}\text{Hf}/^{177}\text{Hf})_{\text{S}} - (^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}}}{(^{176}\text{Hf}/^{177}\text{Hf})_{\text{S}} - (^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}}} \right] \right\} / \left[\frac{(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR}} - (^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}}}{(^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}}} \right],$$

$$T_{\text{DM}}^{\text{C}} = T_{\text{DM}} - (T_{\text{DM}} - t) \times (f_{\text{cc}} - f_{\text{S}}) / (f_{\text{cc}} - f_{\text{DM}}),$$

$$f_{\text{Lu/Hf}} = (^{176}\text{Lu}/^{177}\text{Hf})_{\text{S}} / (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} - 1,$$

where, $\lambda = 1.867 \times 10^{-11} \text{ year}^{-1}$ (Soderlund et al., 2004); $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{S}}$ and $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{S}}$ are the measured values of the samples; $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} = 0.0332$ and $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR}, 0} = 0.282772$ (Blichert-Toft and Albarède, 1997); $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}} = 0.0384$ and $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}} = 0.28325$ (Griffin et al., 2002); $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{mean crust}} = 0.015$; $f_{\text{cc}} = \left[\frac{(^{176}\text{Lu}/^{177}\text{Hf})_{\text{mean crust}}}{(^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}}} - 1 \right]$; $f_{\text{S}} = f_{\text{Lu/Hf}}$; $f_{\text{DM}} = \left[\frac{(^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}}}{(^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}}} - 1 \right]$; and $t =$ crystallization time of zircon.

arc belt to the north and the Aqishan–Yamansu arc belt to the south, as evidenced by the positive bulk $\varepsilon_{\text{Nd}}(t)$ and zircon $\varepsilon_{\text{Hf}}(t)$ values of the Silurian–Carboniferous granitoids and volcanic rocks in eastern Tianshan (Tang et al., 2010; Lei et al., 2011; Zhao et al., 2015); and a post-collisional stage since the Early Permian, as supported by the presence of the youngest ophiolite of ~310 Ma along with widespread bimodal volcanic rocks of ~290 Ma (Qin et al., 2011; Su et al., 2012; Zhang et al., 2015b). Numerous Cu (\pm Ni), Mo, Au, Fe, and Ag metal deposits and associated magmatic rocks were formed in the periods of subduction and post-collisional tectonism.

Previous studies have shown that throughout the stage of the ancient Tianshan ocean subduction, a double subduction of the ancient Tianshan oceanic plate could have occurred during the Silurian to Carboniferous (Han et al., 2006; Xiao et al., 2010, 2013). The Re concentrations of four molybdenite samples from the Yuhai deposit range from 2.1×10^{-5} to 8.3×10^{-5} , with an average of 3.7×10^{-5} (Table 3), which suggests a mixing origin of the mantle and crust (Mao et al., 1999). Zang (2014) argued that the $\delta^{34}\text{S}$ values of sulfide minerals in the Yuhai deposit exhibit a narrow range (-1.3 to +0.3 ‰), which indicates a magmatic source of the sulfur (-3 to +3‰; Chaussidon and Lorand, 1990). Therefore, combined with the regional geological history and our new isotopic age data, we posit that the ancient Tianshan oceanic plate subducted northward beneath the Dananhu–Tousuquan island arc belt and southward beneath the Aqishan–Yamansu island arc belt. Under that subduction-related tectonic setting, the metasomatized mantle magma was emplaced into the shallow crust and induced the formation of the Yuhai intrusions and Cu–Mo deposit, and during that period, the hydrothermal fluids of enriched sulfides possibly played a crucial role in Cu–Mo mineralization.

6. Conclusions

- (1) LA-ICP-MS zircon U–Pb dating indicates that magmatic events occurred at ca. 441–430 Ma in the Yuhai area, and the associated

porphyry Cu–Mo deposit formed later than the emplacement of the diorite and granodiorite.

- (2) The geochemical and Hf isotopic data for the diorites and granodiorites in the Yuhai porphyry Cu–Mo deposit indicate that the host rocks were probably derived from the partial melting of the subduction-modified mantle components.
- (3) Based on the regional geological history, new geochronological and geochemical data, we suggest that the Yuhai intrusions and the associated porphyry Cu–Mo mineralization in eastern Tianshan were generated in an arc setting and that they were likely the result of the northward subduction of the ancient Tianshan oceanic plate beneath the Dananhu–Tousuquan arc belt during the Silurian to Carboniferous.

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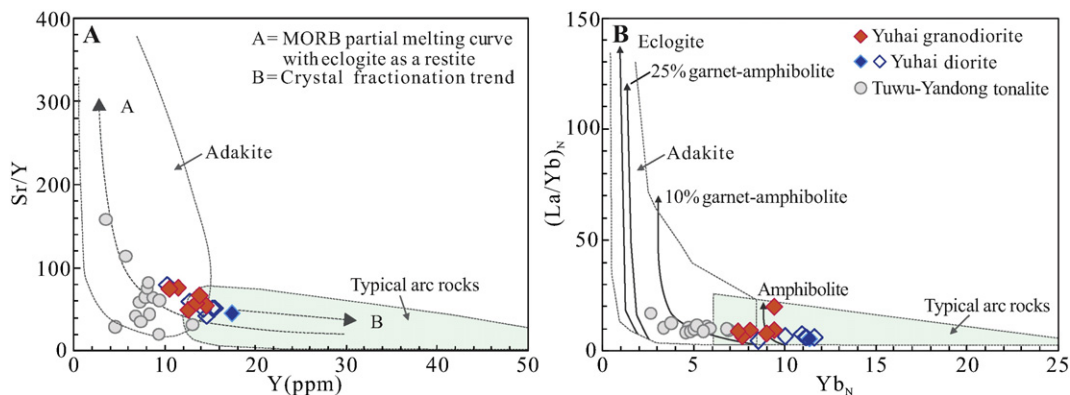


Fig. 12. Plots of Sr/Y vs. Y diagram (A), and $(\text{La}/\text{Yb})_{\text{N}}$ vs. Yb_{N} diagram (B) for the Yuhai intrusions. N means normalized to chondrite (Sun and McDonough, 1989). Modified from Defant and Drummond (1990). Data for the Tuwu–Yandong tonalite are from Wang et al. (2015b,c), and Shen et al. (2012).

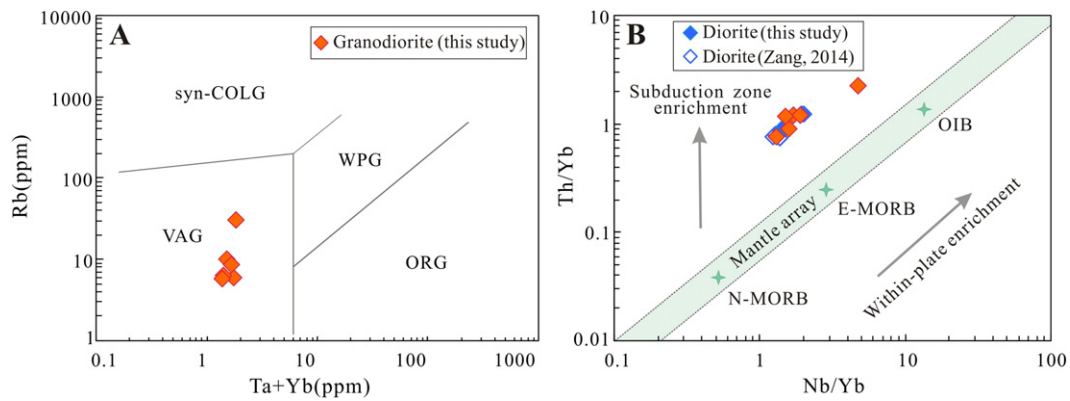


Fig. 13. Tectonic discrimination diagrams for the Yuhai intrusions. (A) Rb vs. Ta + Yb diagram (Pearce et al., 1984); (B) Th/Yb vs. Nb/Yb diagram (Pearce and Peate, 1995; Sayit and Goncuoglu, 2009). WPG, within-plate granitoid; VAG, volcanic arc granitoid; Syn-COLG, syn-collision granitoid; Post-COLG, post-collision granitoid; ORG, ocean ridge granitoid.

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