

Article

Petrogenesis of the Weideshan Pluton in Jiaodong and Its Implications for Gold Polymetallic Mineralization: Constraints from Zircon U-Pb-Hf Isotopes, Petrogeochemistry, and Whole-Rock Sr-Nd Isotopes

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Abstract: The Early Cretaceous Weideshan granites are associated with large-scale Au and polymetallic Cu-Mo-Pb-Zn mineralization. To investigate the petrogenesis of the Weideshan granite and constrain its tectonic setting during the Early Cretaceous, we conducted a zircon U-Pb-Hf isotope and whole-rock geochemical and Sr-Nd isotopic study of the granite. In situ zircon U-Pb dating of three granite samples yielded Early Cretaceous ages of 112.83 ± 0.80 , 112.64 ± 0.91 , and 111.82 ± 0.78 Ma. The samples had high-K calc-alkaline compositions and were enriched in the light rare earth and large-ion lithophile elements (e.g., K, Rb, Ba, Th, and U) and depleted in high-field-strength elements (e.g., Nb, Ti, and P). The samples had small negative Eu anomalies and initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $\epsilon_{\text{Nd}}(t)$ values of 0.70853–0.71029 and –18 to –14, respectively. The zircon $\epsilon_{\text{Hf}}(t)$ values varied between –16 and –12, with corresponding two-stage model ages (t_{DM2}) of 2180–2000 Ma. These characteristics indicated that the Weideshan pluton was formed in a back-arc extensional environment caused by subduction of the Paleo-Pacific Plate toward the Asian continent during the early Cretaceous. The magma was generated by crust–mantle interaction during lithospheric thinning. The diagenetic age of the Weideshan granites was the same as the formation age of gold and polymetallic ores in the Jiaodong area. The extensive fluid circulation induced by the magma emplacement may be the main source of ore-forming materials for the gold and polymetallic Cu-Mo-Pb-Zn deposits.

Keywords: Weideshan pluton; zircon U-Pb age; Sr-Nd isotopes; crust–mantle source; gold and polymetallic mineralization



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1. Introduction

Large-scale crustal thinning occurred in eastern China during the late Mesozoic [1–4]. Asthenospheric upwelling led to intense magmatism and polymetallic mineralization, including Au, Cu, Mo, Ag, Pb, Zn, and rare earth element deposits [5–10]. Especially, the large-scale intermediate-silicic magmatism during 130–110 Ma was very intense and controlled the formation of many Au and other non-ferrous metallic deposits in the Jiaodong area [11–18] (e.g., Jiaojia Au deposit, Linglong Au deposit, Sanshandao Au deposit, Chenjiabu Cu deposit, Tongjiazhuang Ag deposit, Shangjiazhuang Mo deposit, and Xiangkuang Pb-Zn deposit).

The Jiaodong Peninsula contains the main Au deposits in China, with 16 super-large and more than 100 medium and large Au deposits having been discovered, comprising >25% of the total Au reserves in China. The relationship between the formation of Au deposits and late Mesozoic magmatism has been widely studied worldwide. Some

scholars have put forward opinions that the Au deposits in the northwest Jiaodong Peninsula are migmatization-magmatic-hydrothermal deposits related to the Linglong granites [19], whereas others have suggested a post-magmatic hydrothermal origin related to the Guojialing granites [19,20]. Other previous studies have noted that lamprophyres derived from the mantle are genetically related to Au mineralization [21–23]. However, the age of Weideshan granite (127–105 Ma) [24–27] is the same as the age of Au deposits (123–110 Ma) [9,14,18,28–30], which suggests that the Jiaodong gold mineralization is closely related to the magmatic activities of the Weideshan granites [31,32]. In addition, the Weideshan granites are closely related to Cu, Mo, Pb–Zn, and Ag mineralization in the central-eastern Jiaodong Area. Molybdenum, Mo–W, and Cu–Pb–Zn–Au (Ag) polymetallic deposits occur in the inner part of the Weideshan granitic intrusion, along its contacts with surrounding rocks, and in country rocks proximal to the granite. There are porphyry-type deposits in the granite, skarn deposits at the contacts with surrounding rocks, and hydrothermal vein deposits in the country rocks. The Mo(W)–Cu–Pb(Zn)–Au (Ag) polymetallic deposits formed from the inner to the outer parts of the Weideshan granites [25,31] and were genetically related to the granitic intrusions. The magmatic and mineralization ages are similar. For example, the Re–Os isotopic ages of molybdenite of Shangjiazhuang Mo deposit are 115.5 ± 1.6 and 117.6 ± 1.6 Ma [33], the ore-bearing porphyry age of the Xianguang Pb–Zn deposit is 120.6–127.6 Ma [34], and the mineralization age of the Fanjiabu Au deposit in Weihai is ca. 120 Ma [35].

The Weideshan granites are Early Cretaceous in age and are spatially and temporally closely related to large-scale Au and polymetallic mineralization. They are also related to major geological events in the North China Craton, such as crustal extension and lithospheric thinning. The Weideshan granites appear as more than 20 large plutons and 30 types of intrusive rocks. As a typical representative of Weideshan granites, the Weideshan pluton has gradually become a research hot spot. Previous studies of the Weideshan pluton have determined its age [25,27,36,37], as well as its geochemical characteristics and petrogenesis [38–40]. However, there have been few systematic studies of the Weideshan pluton. In this study, we made petrographic and mineralogical observations and obtained whole-rock major and trace element and Sr–Nd–Hf isotope data and zircon U–Pb ages for the Weideshan pluton in Rongcheng. We used these data to constrain the petrogenesis of the granite and its relationship to gold-polymetallic mineralization.

2. Geological Setting and Samples

2.1. Geological Setting

The Jiaodong area is located east of the Tanlu Fault in the eastern North China Craton (Figure 1a) [8]. It is part of the Mesozoic–Cenozoic continental margin zone of the western part of the coastal Pacific mineralization belt. The North China Craton, with an Archean core of 2.5–3.8 Ga, is the largest and oldest craton in China. Based on lithological, geochemical, and metamorphic P–T–t path studies of the basement rocks, this craton can be divided into three parts (Figure 1a): the Eastern Block, the Western Block, and the Trans-North China Orogen [8]. The Jiaodong area contains the Jiaobei uplift of the North China Craton and the Weihai–Jiaonan uplift of the Dabie–Sulu orogenic belt, which are bounded by the Wulian–Qingdao and Muping–Jimo faults. The Tanlu fault system comprises mainly (N)NE–(S)SW-trending faults and minor E–W and NEE–SWW-trending faults (Figure 1b) [31]. The E–W-trending faults are poorly exposed in the study area. The outcropping rocks in the Jiaodong area, from oldest to youngest, are Paleo–Neoproterozoic metamorphic rocks, Cretaceous volcanic-sedimentary rocks, and Quaternary sediments. Magmatic rocks in the Jiaodong area are widely developed, mainly concentrated in Archean and Mesozoic, among which 2.9 Ga, 2.7 Ga, and 2.5 Ga TTG rock series developed in the Archean. Mesozoic magmatic rocks include late Jurassic Linglong granite, early Cretaceous Guojialing granite, late early Cretaceous Weideshan granite and Laoshan granite, and some silicic-intermediate dikes (Figure 1b).

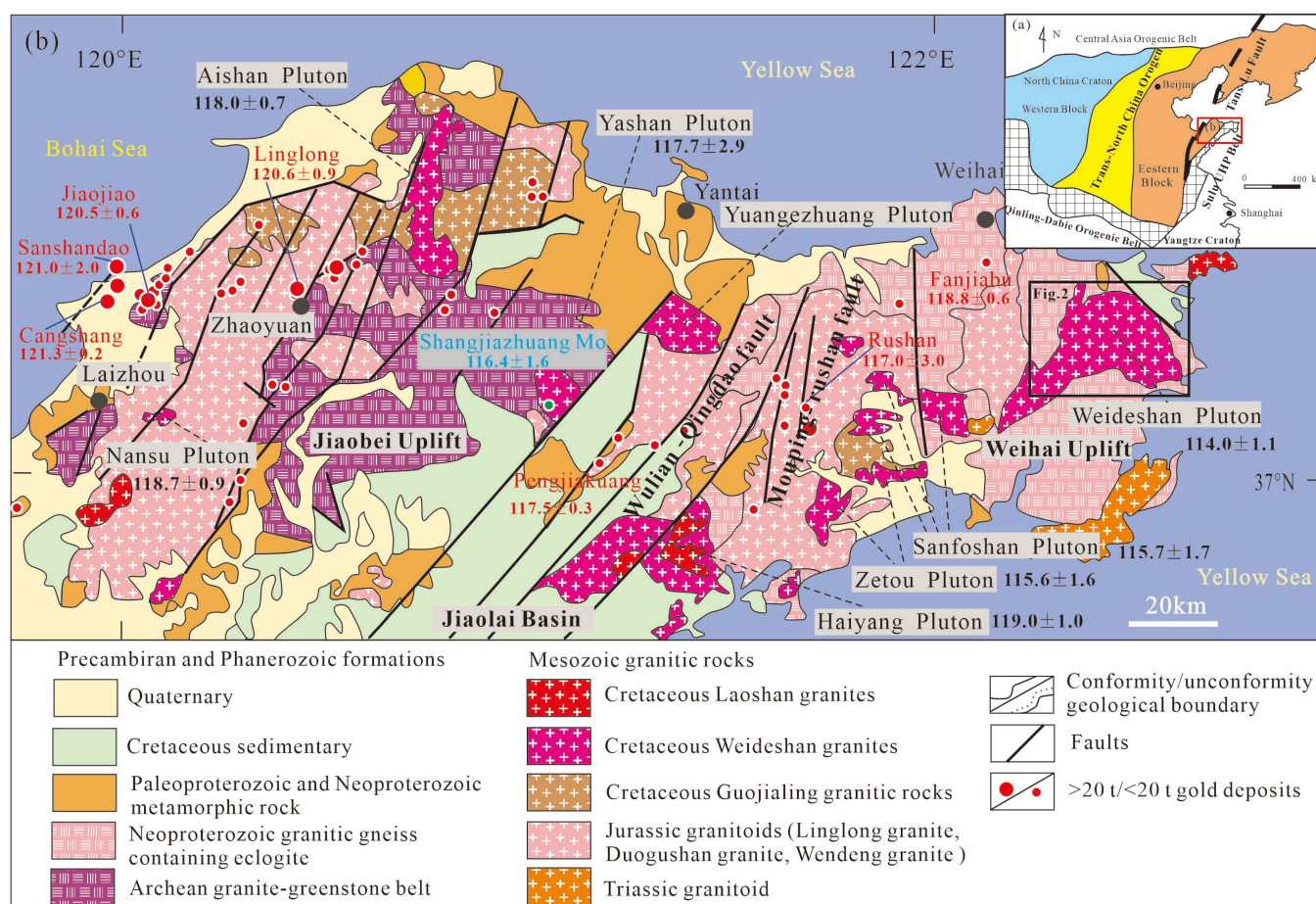


Figure 1. Simplified geological map of the North China Craton (a) (modified after [8]) and geologic and tectonic map of the Jiaodong area (b) (modified after [31]). (Source of data: mineralization ages after [9,33,35]; crystallization ages after [24–27].)

The Weideshan granites are the most abundant magmatic rock type in the Cretaceous, mainly consisting of intermediate-silicic intrusive rocks. They cover a large area of about 1435 km² (Figure 1) and are divided into several plutons such as Weideshan, Sanfoshan, Yashan and Aishan, Yuangezhuang, and Haiyang. Generally, the granite has the form of a composite batholith comprising multiple stocks that trend (N)NE–(S)SW. From west to east, the proportion of granitic material increases. Among them, the Weideshan pluton itself in Rongcheng City is a typical representative, located in the central part of the Weihai uplift, with a horsehead shape facing west on the map (Figure 2) [25]. It intrudes from SE to NW and is centered on the east of Lengjia. From oldest to youngest, it is divided into the Guzhuang unit (fine-grained hornblende quartz diorite), Luoxitou unit (porphyritic medium-grained hornblende quartz monzonite), Dashuipo unit (porphyritic medium-grained amphibole quartz monzonite), Bulujiang unit (medium-grained amphibole quartz monzonite with huge phenocryst), Yaxi unit (porphyritic medium-grained amphibole monzonite), and Hutoushi unit (fine-grained monzogranite).

2.2. Samples

In this study, we conducted a field investigation and sampling of the Weideshan pluton in Rongcheng (sampling locations are shown in Figure 2). All samples were collected from field outcrops, and the rock samples were relatively fresh by hand specimens (Figure 3). There were three groups of rock samples in total, with each group including five samples taken from different outcrops in a small area. Among them, two groups of samples were collected from a quarry in Huanggou village, Rongcheng City (serial numbers WDS-01 and

WDS-02), and their lithologies were medium-grained monzogranite and biotite-bearing monzogranite, respectively, belonging to the Yaxi unit. Another group of samples was collected from Suijia village, Matai, Rongcheng City (WDS-03), consisting of porphyritic fine-grained monzogranite, belonging to the Buluogang unit.

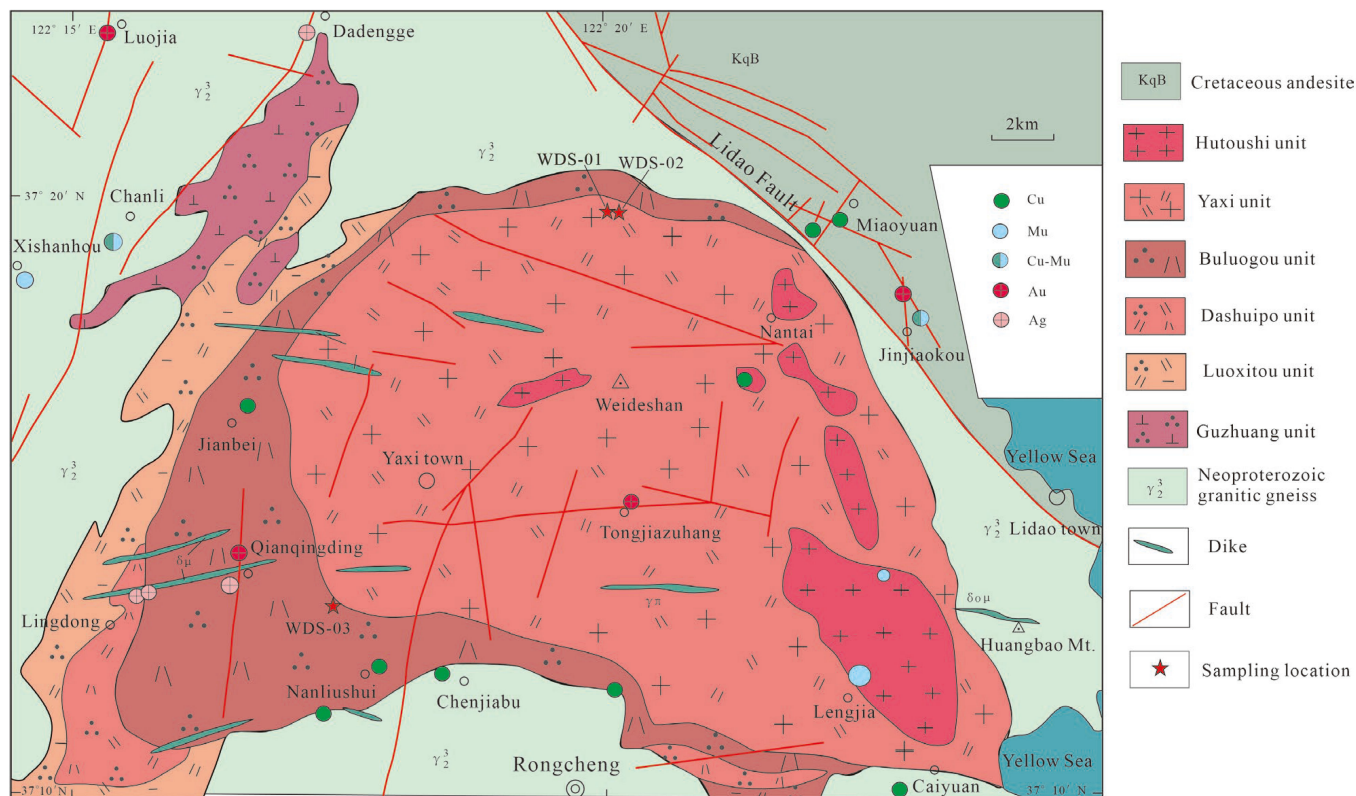


Figure 2. Geologic map of Weideshan pluton in the Rongcheng area, Jiaodong (modified after [25]).

The medium-grained monzogranite (WDS-01 and WDS-03) was gray-white to light pink in color, had a medium-grained granitic texture (Figure 3a,c), and was massive in structure. It consisted mainly of K-feldspar (30–35 vol.%), plagioclase (25–30 vol.%), and quartz (25–30 vol.%) (Figure 3d,f) and lesser biotite (1–5 vol.%) and amphibole (1–3 vol.%) (Figure 3d,f), along with accessory zircon and magnetite (Figure 3g). The K-feldspar had a hypidiomorphic-xenomorphic granular texture and occasional Carlsbad twins (Figure 3f). The plagioclase had an idiomorphic-hypidiomorphic platy shape, surficial sericitization, multiple twinning, and some zoning (Figure 3g). Quartz was intergranular and had a variable grain size (Figure 3f). Biotite occurred along the rims of quartz and feldspar (Figure 3d). The amphibole had an idiomorphic or hypidiomorphic texture (Figure 3f).

The porphyritic biotite-bearing monzogranite (WDS-02) was gray-white in color and had a fine-grained granitic texture (Figure 3b) and massive structure. It consisted mainly of plagioclase (35–40 vol.%), K-feldspar (25–33 vol.%), quartz (25–30 vol.%), and biotite (5–8 vol.%), along with accessory magnetite, apatite, and zircon (Figure 3e,h). The K-feldspar phenocrysts were 0.5–1.0 cm in size and light pink in color. The matrix consisted of 0.1–0.5 mm sized felsic and mafic minerals. The plagioclase had an idiomorphic-hypidiomorphic platy shape and exhibited multiple twinning and zoning (Figure 3h). Biotite occurred along the quartz and feldspar crystal rims (Figure 3e).

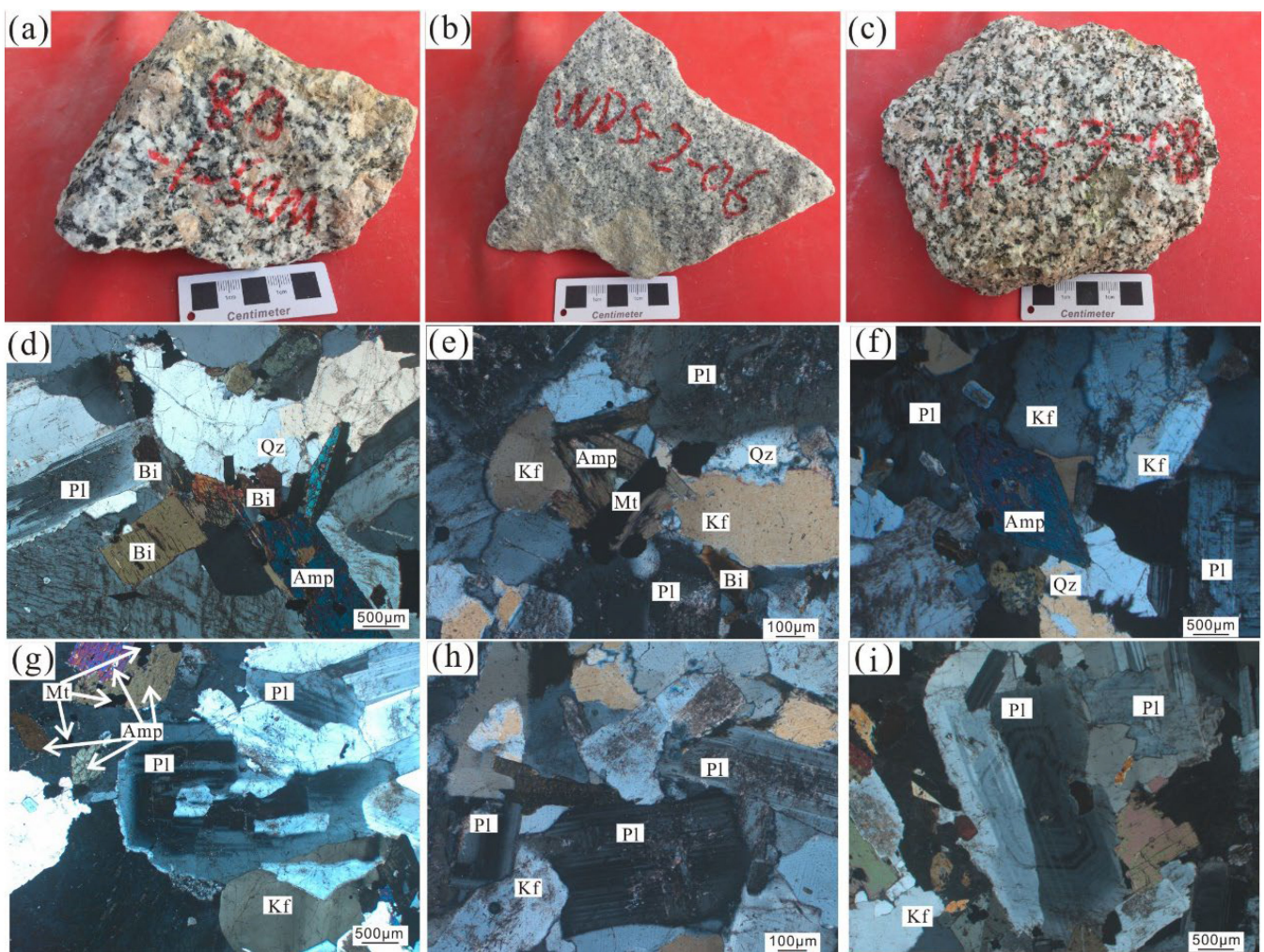


Figure 3. Petrological characteristics of the Weideshan pluton. (a) WDS-01 hand specimen. (b) WDS-02 hand specimen. (c) WDS-03 hand specimen. (d) WDS-01 microscopic characteristics, granitic texture. (e) WDS-02 microscopic characteristics, granitic texture. (f) WDS-03 microscopic characteristics, granitic texture. (g) WDS-01 microscopic characteristics, plagioclase zoning. (h) WDS-02 microscopic characteristics, plagioclase zoning texture. (i) WDS-03 microscopic characteristics, plagioclase polysynthetic twins. Qz—quartz; Kf—potassium feldspar; Pl—plagioclase; Amp—amphibole; Bi—biotite; Mt—magnetite.

3. Methods

3.1. Zircon Separation and LA-ICP-MS U-Pb Dating

Zircon separation was conducted at Langfang Fengzeyuan Rock and Mineral Testing Technology Co., Ltd. (Langfang, China). Fresh samples were selected and washed by purified water after removal of surface weathering. The samples were mechanically crushed to 80 mesh, and then zircons were separated by magnetic and heavy liquid techniques and hand-picking.

Zircon mounting and selection using transmitted light and cathodoluminescence (CL) images and LA-ICP-MS analysis were undertaken at Beijing Createch Testing Technology Co., Ltd. (Beijing, China). Zircons were selected under the binoculars, mounted in epoxy resin, and then polished to expose grain mid-sections. Before analysis, the grains were carefully observed through transmitted light and CL to select the ones with no cracks, no inclusions, and good growth zones for age dating. The mount-making procedures were described by Song Biao et al. [41]. The analyses were conducted with a New Wave 193 nm FX laser coupled to a Thermo Fisher Neptune multiple-collector-inductively coupled

plasma-mass spectrometer (MC-ICP-MS). The laser beam diameter was 35 μm , and the carrier gas was He. The analytical procedures were described by Yuan et al. [42]. The results were corrected for U-Th-Pb isotopic fractionation and the presence of common Pb (from the measured ^{204}Pb). The final data were processed with ICP-MS DataCal software [43]. Zircon U-Pb concordia diagrams and weighted-mean ages were obtained with the Isoplot 3.0 software [44]. The data are listed in Table 1.

3.2. Major and Trace Element Analyses

The analysis of total rock major and trace elements was performed by Beijing Createch Testing Technology Co., Ltd. (Beijing, China). Fresh samples of Weideshan pluton were selected and crushed to less than 200 mesh. Major elements were analyzed on fused glass disks by X-ray fluorescence spectrometry (XRF), with an accuracy of better than 1%. The fused glass disks were prepared by mixing the samples with $\text{Li}_2\text{B}_4\text{O}_7\text{-LiBO}_2$ flux, with an automated fusion system. The trace elements were determined by using an inductively coupled plasma mass spectrometer (ICP-MS). The samples were mixed with LiBO_2 flux, placed in a furnace at $>1000^\circ\text{C}$, cooled, and dissolved in nitric acid prior to analysis. The analytical accuracy was better than 5%. The analytical results are listed in Table 2.

3.3. Strontium-Neodymium Isotopes

The whole-rock Sr and Nd isotopes were determined at Beijing Kehui Testing Technology Co., Ltd. (Beijing, China). Samples were weighted into Teflon capsules along with ^{84}Sr , ^{87}Rb , ^{150}Nd , and ^{147}Sm isotopic spikes and then digested in HClO_4 and HF. After ion exchange separation, the Sr-Nd isotope ratios were measured with a Finnigan MAT 262 thermal ionization mass spectrometer. The chemical separation procedures were described by Zhang et al. [45]. The Sr and Nd isotope ratios were normalized to $^{87}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively. The procedural blanks for Rb and Sr were <100 pg, and for Sm and Nd they were <50 pg. The obtained standard results were as follows: NBS-987 $^{87}\text{Sr}/^{86}\text{Sr} = 0.710248 \pm 13$; GSB $^{143}\text{Nd}/^{144}\text{Nd} = 0.512185 \pm 8$. The data are listed in Table 3.

3.4. Zircon Hf Isotopes

Zircon Hf isotope analysis was performed at Beijing Createch Testing Technology Co., Ltd. (Beijing, China) with a Neptune MC-ICP MS system, on or close to the U-Pb dating spots. The laser and mass spectrometer were the same as those used for the zircon U-Pb dating. The analytical conditions, instrument settings, and procedures were described by Geng et al. [46]. The $\epsilon_{\text{Hf}}(t)$ values were calculated using the zircon U-Pb ages for each individual spot. In this paper, the adopted ^{176}Lu decay constant was $1.867 \times 10^{-11} \text{ year}^{-1}$ [47], the $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of chondrite was 0.0332, and the $^{176}\text{Lu}/^{177}\text{Hf}$ ratio was 0.282772 [48]. Depleted mantle model ages (t_{DM1}) were calculated based on present-day depleted mantle values of $^{176}\text{Lu}/^{177}\text{Hf} = 0.0384$ and $^{176}\text{Hf}/^{177}\text{Hf} = 0.28325$ [49]. The ratio of $^{176}\text{Lu}/^{177}\text{Hf} = 0.015$ for the average crust [50] was used to calculate the depleted mantle model age (t_{DM2}). The data are listed in Table 4.

Table 1. LA-ICP-MS zircon U-Pb dating of the Weideshan pluton.

Point Number	Content (×10 ⁻⁶)			²³² Th / ²³⁸ U	Ratio/Deviation					Age(Ma)/Deviation				Concordance	
	Th ²³²	U ²³⁸	Pb		²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U		1σ
WDS-01-1 Medium-grained monzogranite															
WDS-01-1-01	686.0	544.4	67.30	0.01	0.0508	0.0015	0.1213	0.003	0.0174	0.0002	116	3	111	1	95%
WDS-01-1-02	394.4	433.3	40.18	0.02	0.0483	0.0019	0.1169	0.004	0.0176	0.0003	112	4	113	2	99%
WDS-01-1-03	731.1	556.6	70.98	0.01	0.0492	0.0014	0.1198	0.003	0.0177	0.0002	115	3	113	1	98%
WDS-01-1-04	506.3	453.1	50.91	0.02	0.0497	0.0018	0.1210	0.004	0.0177	0.0002	116	4	113	1	97%
WDS-01-1-05	617.7	420.4	61.40	0.02	0.0462	0.0012	0.1130	0.003	0.0177	0.0003	108	3	113	2	95%
WDS-01-1-06	531.2	515.1	52.23	0.02	0.0495	0.0016	0.1167	0.004	0.0172	0.0002	112	3	110	1	98%
WDS-01-1-08	811.9	697.4	79.31	0.01	0.0476	0.0012	0.1140	0.003	0.0174	0.0002	110	2	111	1	98%
WDS-01-1-09	908.8	867.3	87.37	0.01	0.0480	0.0012	0.1136	0.003	0.0171	0.0002	109	2	109	1	99%
WDS-01-1-10	398.3	353.1	37.87	0.02	0.0462	0.0015	0.1117	0.004	0.0175	0.0002	107	3	112	1	95%
WDS-01-1-11	518.5	406.7	49.75	0.02	0.0532	0.0022	0.1256	0.005	0.0171	0.0003	120	4	109	2	91%
WDS-01-1-12	555.2	451.5	52.78	0.02	0.0533	0.0017	0.1289	0.004	0.0175	0.0002	123	3	112	1	90%
WDS-01-1-13	652.6	516.7	62.95	0.01	0.0459	0.0012	0.1115	0.003	0.0177	0.0002	107	2	113	1	94%
WDS-01-1-14	726.5	751.5	73.08	0.01	0.0490	0.0014	0.1202	0.004	0.0177	0.0002	115	3	114	1	98%
WDS-01-1-15	683.5	616.3	65.95	0.01	0.0469	0.0015	0.1164	0.003	0.0181	0.0002	111	3	116	1	96%
WDS-01-1-16	678.2	844.9	68.53	0.01	0.0509	0.0015	0.1203	0.004	0.0171	0.0002	115	31	107	1	94%
WDS-01-1-18	855.0	595.6	77.38	0.01	0.0474	0.0013	0.1152	0.003	0.0176	0.0002	110	3	112	1	98%
WDS-01-1-19	175.6	176.8	17.08	0.05	0.0486	0.0023	0.1188	0.006	0.0177	0.0002	114	5	113	1	99%
WDS-01-1-20	521.5	522.3	53.03	0.02	0.0478	0.0012	0.1192	0.003	0.0180	0.0002	114	3	115	1	99%
WDS-01-1-21	337.1	311.3	33.71	0.03	0.0522	0.0016	0.1276	0.004	0.0176	0.0002	122	4	113	1	92%
WDS-01-1-22	288.7	280.5	28.92	0.03	0.0484	0.0021	0.1176	0.005	0.0177	0.0002	113	5	113	1	99%
WDS-01-1-23	414.5	365.0	40.74	0.02	0.0486	0.0015	0.1202	0.004	0.0179	0.0002	115	3	114	1	99%
WDS-01-1-24	445.0	337.7	42.93	0.02	0.0478	0.0017	0.1181	0.004	0.0179	0.0002	114	4	115	1	98%
WDS-01-1-25	298.1	237.5	29.21	0.03	0.0448	0.0022	0.1119	0.006	0.0180	0.0002	108	5	115	1	93%

Table 1. Cont.															
Point Number	Content ($\times 10^{-6}$)			^{232}Th $/^{238}\text{U}$	Ratio/Deviation						Age(Ma)/Deviation				Concordance
	Th ²³²	U ²³⁸	Pb		$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	
WDS-02-1 Porphyritic biotite-bearing monzogranite															
WDS-02-1-01	441.5	455.1	47.08	0.02	0.0491	0.0014	0.1201	0.004	0.0178	0.0002	115	3	114	1	98%
WDS-02-1-02	853.9	730.5	88.22	0.01	0.0463	0.0011	0.1145	0.003	0.0179	0.0002	110	2	115	1	95%
WDS-02-1-03	333.7	355.4	34.91	0.02	0.0484	0.0017	0.1153	0.004	0.0173	0.0002	111	3	111	1	99%
WDS-02-1-04	264.7	258.7	28.16	0.03	0.0507	0.0021	0.1203	0.005	0.0173	0.0002	115	4	11	1	95%
WDS-02-1-05	602.6	575.2	61.69	0.01	0.0483	0.0014	0.1151	0.004	0.0172	0.0002	111	3	110	1	99%
WDS-02-1-06	524.7	622.6	57.82	0.02	0.0469	0.0014	0.1134	0.003	0.0175	0.0002	109	3	112	1	97%
WDS-02-1-08	714.4	616.6	74.13	0.01	0.0489	0.0014	0.1178	0.003	0.0175	0.0002	113	3	112	1	99%
WDS-02-1-10	393.4	395.6	41.50	0.02	0.0511	0.0017	0.1225	0.004	0.0174	0.0002	117	4	112	1	95%
WDS-02-1-11	296.2	863.8	40.93	0.02	0.0495	0.0012	0.1206	0.003	0.0176	0.0002	115	3	113	1	97%
WDS-02-1-12	316.2	285.7	33.28	0.03	0.0491	0.0021	0.1205	0.005	0.0179	0.0002	115	4	114	2	98%
WDS-02-1-13	355.6	340.3	38.51	0.02	0.0503	0.0022	0.1271	0.005	0.0184	0.0003	121	5	117	2	96%
WDS-02-1-14	449.5	430.8	47.14	0.02	0.0502	0.0022	0.1152	0.005	0.0167	0.0002	110	4	107	1	96%
WDS-02-1-15	331.9	362.0	37.72	0.03	0.0461	0.0017	0.1157	0.005	0.0180	0.0002	111	4	115	1	96%
WDS-02-1-16	309.2	247.9	31.51	0.03	0.0481	0.0021	0.1154	0.004	0.0175	0.0003	110	4	112	2	98%
WDS-02-1-17	577.1	487.2	63.82	0.02	0.0474	0.0016	0.1218	0.004	0.0187	0.0002	117	4	119	1	97%
WDS-02-1-18	529.9	473.2	56.30	0.02	0.0488	0.0015	0.1213	0.004	0.0179	0.0002	116	4	115	1	98%
WDS-02-1-19	470.0	435.3	50.11	0.02	0.0494	0.0016	0.1258	0.004	0.0184	0.0002	120	4	118	1	98%
WDS-02-1-20	804.0	701.7	86.50	0.01	0.0513	0.0016	0.1264	0.004	0.0179	0.0002	121	3	114	1	94%
WDS-02-1-21	473.2	378.3	47.82	0.02	0.0496	0.0019	0.1183	0.004	0.0173	0.0002	113	4	110	1	97%
WDS-02-1-22	265.5	239.0	28.38	0.03	0.0476	0.0022	0.1202	0.006	0.0183	0.0002	115	5	117	1	98%
WDS-02-1-23	555.5	597.2	59.92	0.02	0.0505	0.0016	0.1227	0.004	0.0176	0.0002	117	3	112	1	95%
WDS-02-1-24	319.9	312.5	35.65	0.03	0.0508	0.0017	0.1241	0.004	0.0177	0.0002	119	4	113	1	95%
WDS-03-1 Medium-grained monzogranite															
WDS-03-1-01	379.8	343.6	40.02	0.02	0.0488	0.0016	0.1172	0.004	0.0174	0.0002	112	3	111	1	99%

Table 1. Cont.

Point Number	Content ($\times 10^{-6}$)			^{232}Th $/^{238}\text{U}$	Ratio/Deviation						Age(Ma)/Deviation				Concordance
	Th^{232}	U^{238}	Pb		$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	
WDS-03-1-02	477.8	417.5	47.97	0.02	0.0497	0.0014	0.1161	0.003	0.0169	0.0002	111	3	108	1	97%
WDS-03-1-03	497.7	442.7	50.42	0.02	0.0491	0.0014	0.1143	0.004	0.0169	0.0002	109	3	108	1	98%
WDS-03-1-04	672.9	424.1	62.57	0.01	0.0522	0.0015	0.1248	0.004	0.0173	0.0002	119	3	111	1	92%
WDS-03-1-05	462.1	436.8	44.58	0.02	0.0492	0.0017	0.1151	0.004	0.0170	0.0002	111	3	109	1	98%
WDS-03-1-06	705.9	554.5	68.18	0.01	0.0478	0.0013	0.1163	0.003	0.0176	0.0002	112	3	113	1	98%
WDS-03-1-07	297.6	270.5	31.26	0.03	0.0523	0.0023	0.1276	0.006	0.0178	0.0002	122	5	114	1	93%
WDS-03-1-08	310.9	302.9	31.37	0.03	0.0502	0.0018	0.1181	0.004	0.0171	0.0002	113	3	109	1	96%
WDS-03-1-09	385.3	353.0	37.82	0.02	0.0478	0.0017	0.1124	0.004	0.0171	0.0002	108	3	109	1	98%
WDS-03-1-10	348.5	287.3	35.52	0.03	0.0517	0.0032	0.1231	0.007	0.0174	0.0002	117	6	111	1	94%
WDS-03-1-11	442.1	397.3	46.16	0.02	0.0515	0.0019	0.1271	0.005	0.0179	0.0002	121	4	115	1	94%
WDS-03-1-12	440.0	506.2	47.36	0.02	0.0521	0.0018	0.1254	0.004	0.0175	0.0002	119	3	112	1	93%
WDS-03-1-13	329.7	258.7	33.76	0.03	0.0461	0.0018	0.1130	0.005	0.0177	0.0002	108	4	113	1	95%
WDS-03-1-14	717.9	527.5	70.18	0.01	0.0488	0.0015	0.1134	0.004	0.0168	0.0002	109	3	108	1	98%
WDS-03-1-15	326.4	296.4	33.79	0.03	0.0492	0.0022	0.1193	0.006	0.0176	0.0002	114	5	112	1	98%
WDS-03-1-16	313.3	282.4	31.73	0.03	0.0506	0.0021	0.1198	0.005	0.0172	0.0002	114	4	110	1	95%
WDS-03-1-17	491.7	402.2	49.28	0.02	0.0528	0.0020	0.1263	0.005	0.0173	0.0002	120	4	111	1	91%
WDS-03-1-18	285.5	287.4	29.15	0.03	0.0475	0.0019	0.1133	0.005	0.0172	0.0002	109	4	110	1	98%
WDS-03-1-19	359.5	346.6	36.73	0.03	0.0503	0.0018	0.1236	0.004	0.0179	0.0002	118	3	114	1	96%
WDS-03-1-20	561.5	478.0	60.19	0.02	0.0476	0.0016	0.1214	0.004	0.0185	0.0002	116	3	118	1	98%
WDS-03-1-21	424.0	361.6	44.46	0.02	0.0478	0.0019	0.1168	0.005	0.0177	0.0002	112	4	113	1	99%
WDS-03-1-22	491.8	400.7	50.05	0.02	0.0459	0.0013	0.1123	0.004	0.0177	0.0002	108	3	113	1	95%
WDS-03-1-23	808.3	827.3	95.39	0.01	0.0488	0.0012	0.1393	0.004	0.0207	0.0003	132	3	132	2	99%
WDS-03-1-24	343.7	313.1	34.36	0.03	0.0537	0.0021	0.1287	0.005	0.0174	0.0002	123	4	111	1	90%
WDS-03-1-25	487.3	434.9	54.27	0.02	0.0546	0.0023	0.1288	0.006	0.0174	0.0003	123	5	112	2	90%

Table 2. Contents of major elements (wt.%) and trace elements (ppm) of the Weideshan pluton.

Number	WDS-01-2	WDS-01-4	WDS-01-6	WDS-01-8	WDS-01-10	WDS-02-2	WDS-02-4	WDS-02-6	WDS-02-8	WDS-02-10	WDS-03-2	WDS-03-4	WDS-03-6	WDS-03-8	WDS-03-10
Lithology	Medium-grained monzogranite					Porphyritic biotite-bearing monzogranite					Medium-grained monzogranite				
SiO ₂	69.27	70.10	69.14	70.26	69.78	72.29	72.45	72.07	72.37	72.67	68.01	67.26	67.95	68.56	67.58
Al ₂ O ₃	14.68	14.53	14.55	14.61	14.51	14.97	15.20	15.00	14.93	15.08	14.99	15.00	14.70	14.61	14.88
MgO	1.49	1.37	1.75	1.52	1.45	0.40	0.45	0.43	0.44	0.45	1.81	2.03	2.00	1.79	2.01
Na ₂ O	4.14	3.95	4.17	4.18	3.64	4.27	4.38	4.32	4.36	4.40	4.04	4.13	4.13	4.08	3.91
K ₂ O	4.22	4.58	3.63	3.75	5.14	3.92	3.88	3.98	3.96	3.92	4.31	3.90	3.74	3.92	4.33
P ₂ O ₅	0.14	0.12	0.18	0.14	0.14	0.05	0.06	0.06	0.06	0.06	0.17	0.18	0.18	0.17	0.18
TiO ₂	0.31	0.26	0.39	0.29	0.27	0.13	0.14	0.14	0.14	0.14	0.34	0.40	0.39	0.35	0.37
CaO	2.69	2.30	2.95	2.72	2.30	2.00	2.01	1.97	2.01	2.03	2.92	3.27	3.18	3.00	3.14
Fe ₂ O _{3total}	2.65	2.35	3.10	2.65	2.50	1.27	1.27	1.34	1.28	1.28	3.03	3.36	3.29	2.99	3.28
MnO	0.06	0.05	0.06	0.06	0.05	0.02	0.02	0.02	0.02	0.02	0.05	0.05	0.05	0.05	0.05
LOI	0.65	0.45	0.58	0.42	0.46	0.48	0.57	0.67	0.59	0.43	0.76	0.79	0.66	0.74	0.62
TOTAL	100.3	100.1	100.5	100.6	100.2	99.81	100.4	100.00	100.1	100.5	100.4	100.4	100.3	100.2	100.3
Rb	137	143	123	119	149	159	160	157	155	157	128	118	125	128	130
Sr	586	496	513	529	579	402	425	395	401	403	623	639	588	576	616
Ba	1212	1402	736	1101	1736	1725	1801	1705	1751	1763	1593	1265	1169	1116	1330
Th	37.68	21.39	24.31	22.95	22.38	15.31	16.21	15.28	13.78	14.26	24.81	28.68	20.73	27.22	30.16
U	6.65	5.07	4.76	2.69	5.43	4.10	4.55	4.38	3.75	3.98	4.04	8.04	5.14	3.58	3.68
Nb	15.22	15.60	16.23	17.42	16.81	15.49	16.66	16.72	14.72	15.05	19.25	20.43	20.05	18.62	17.08
Ta	1.30	0.94	1.38	0.96	0.94	0.82	1.03	0.83	0.87	0.77	1.03	1.15	1.11	1.02	0.93
Zr	144	116	172	70.06	160	114	113	112	115	120	174	248	152	170	206
Hf	3.65	3.02	4.04	1.87	3.67	2.69	2.79	2.70	2.69	2.79	4.06	5.48	3.64	4.03	4.41
Co	10.75	9.54	12.96	9.25	10.30	2.89	3.15	2.90	2.95	2.98	13.25	14.24	14.24	12.84	14.19
Number	WDS-01-2	WDS-01-4	WDS-01-6	WDS-01-8	WDS-01-10	WDS-02-2	WDS-02-4	WDS-02-6	WDS-02-8	WDS-02-10	WDS-03-2	WDS-03-4	WDS-03-6	WDS-03-8	WDS-03-10
Lithology	Medium-grained monzogranite					Porphyritic biotite-bearing monzogranite					Medium-grained monzogranite				
Ni	21.22	20.28	39.49	17.36	16.46	3.07	8.67	2.52	3.37	2.89	30.06	23.84	23.34	21.56	27.46
Cr	42.30	42.67	80.66	35.82	35.36	9.69	13.24	9.33	12.06	10.72	63.79	51.92	46.85	44.24	53.18
V	48.88	43.16	51.74	23.47	45.57	14.08	13.63	14.35	16.66	14.85	53.66	63.31	66.14	59.21	66.35
Sc	9.97	10.00	11.65	9.45	10.64	4.40	4.62	5.67	4.67	5.00	12.99	13.48	13.48	13.24	14.74
Cs	2.05	2.18	2.30	2.65	2.10	2.95	3.52	3.36	3.25	3.17	1.60	1.49	2.27	1.66	1.94
Ga	51.71	46.48	50.84	47.89	47.05	44.76	46.65	48.08	47.59	47.57	50.50	52.55	52.58	50.67	49.48
Cu	4.55	4.43	6.07	3.45	4.19	5.09	15.22	4.65	4.49	6.31	5.55	4.76	5.45	4.53	5.04
Pb	18.51	17.42	14.90	14.80	17.82	23.30	24.13	20.52	21.71	23.11	16.23	14.14	13.52	14.49	15.14
Zn	39.91	34.42	49.96	36.94	35.56	48.09	22.17	17.27	15.42	16.93	36.98	38.50	39.84	36.07	34.76
Be	2.35	2.25	2.47	2.44	2.04	1.79	1.95	2.67	1.76	1.74	2.29	2.15	2.60	2.45	1.99
La	50.82	33.25	51.19	40.09	37.40	28.60	28.39	29.42	31.58	32.42	50.74	55.04	46.43	48.57	49.28
Ce	87.70	59.91	91.81	69.18	67.04	47.27	47.26	49.29	53.01	53.94	91.57	99.43	86.20	86.26	88.71
Pr	8.23	6.02	9.04	6.63	6.60	4.36	4.33	4.59	4.82	4.95	9.02	9.97	8.77	8.62	8.97
Nd	31.08	23.64	35.19	25.93	26.63	16.07	16.06	17.12	17.58	17.66	35.87	39.53	34.18	33.56	35.71
Sm	4.15	3.29	4.74	3.63	3.56	2.21	2.26	2.34	2.41	2.26	4.83	5.32	4.73	4.58	4.95

Table 2. Cont.

Number	WDS-01-2	WDS-01-4	WDS-01-6	WDS-01-8	WDS-01-10	WDS-02-2	WDS-02-4	WDS-02-6	WDS-02-8	WDS-02-10	WDS-03-2	WDS-03-4	WDS-03-6	WDS-03-8	WDS-03-10
Eu	1.14	1.05	1.09	1.04	1.26	0.88	0.88	0.87	0.90	0.90	1.38	1.37	1.23	1.19	1.37
Gd	3.48	2.72	3.90	3.02	3.04	1.90	1.93	2.05	2.03	1.94	3.92	4.40	3.84	3.67	4.16
Tb	0.37	0.31	0.44	0.35	0.33	0.21	0.22	0.22	0.23	0.21	0.42	0.48	0.42	0.41	0.44
Dy	1.84	1.46	2.10	1.73	1.52	1.05	1.18	0.98	1.08	0.96	1.99	2.26	1.96	1.94	2.09
Ho	0.56	0.30	0.43	0.36	0.33	0.23	0.35	0.20	0.22	0.20	0.41	0.46	0.41	0.40	0.42
Er	1.16	0.80	1.08	0.91	0.85	0.57	0.66	0.51	0.55	0.52	1.02	1.19	1.04	1.02	1.14
Tm	0.25	0.14	0.18	0.15	0.14	0.10	0.15	0.08	0.09	0.09	0.17	0.19	0.15	0.16	0.18
Yb	1.28	0.94	1.25	1.04	1.00	0.65	0.67	0.60	0.62	0.61	1.19	1.35	1.18	1.14	1.25
Lu	0.18	0.15	0.20	0.15	0.16	0.10	0.10	0.10	0.09	0.10	0.18	0.20	0.17	0.18	0.19
Y	11.89	13.12	13.17	15.72	14.61	10.06	10.50	9.34	10.33	9.23	12.54	13.90	12.37	12.05	13.12
Number	WDS-01-2	WDS-01-4	WDS-01-6	WDS-01-8	WDS-01-10	WDS-02-2	WDS-02-4	WDS-02-6	WDS-02-8	WDS-02-10	WDS-03-2	WDS-03-4	WDS-03-6	WDS-03-8	WDS-03-10
Lithology	Medium-grained monzogranite					Porphyritic biotite-bearing monzogranite					Medium-grained monzogranite				
A/CNK	0.90	0.93	0.91	0.92	0.92	1.05	1.01	1.01	0.98	0.99	0.90	0.86	0.88	0.89	0.81
ΣREE	192.2	133.9	202.6	154.2	149.8	104.1	104.4	108.3	115.2	116.7	202.7	221.2	190.7	191.7	198.9
LREE/HREE	20.1	18.7	20.2	19.0	19.3	20.7	18.8	21.8	22.4	24.2	20.7	19.9	19.7	20.4	19.0
La _N /Yb _N	26.8	23.8	27.6	26.0	25.2	29.8	28.4	32.9	34.2	35.6	28.6	27.4	26.4	28.5	26.4
(Eu/Eu*) _N	0.89	1.04	0.76	0.94	1.14	1.29	1.26	1.19	1.21	1.28	0.94	0.84	0.85	0.86	0.89

Table 3. Rb-Sr and Sm-Nd isotopic characteristics of the Weideshan pluton.

Sample Number	Rb ($\times 10^{-6}$)	Sr ($\times 10^{-6}$)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	2σ	Sm ($\times 10^{-6}$)	Nd ($\times 10^{-6}$)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	2σ	$(^{87}\text{Sr}/^{86}\text{Sr})_i$	$\epsilon_{\text{Nd}}(t)$	$t_{\text{DM}}(\text{Ma})$
WDS-01-2	136	585	0.1425	0.708663	0.000006	4.15	31.1	0.1015	0.511911	0.000005	0.708423	−14.1	2641
WDS-01-4	142	496	0.2472	0.708933	0.000007	3.29	23.6	0.0842	0.511906	0.000004	0.708637	−14.2	2480
WDS-01-6	123	513	0.1965	0.708710	0.000007	4.74	35.2	0.0868	0.511905	0.000006	0.708546	−14.3	2392
WDS-01-8	119	529	0.1754	0.708624	0.000008	3.63	25.9	0.0954	0.511905	0.000005	0.708522	−14.3	2571
WDS-01-10	149	579	0.2078	0.708801	0.000005	3.56	26.7	0.0936	0.511914	0.000005	0.708762	−14.1	2502
WDS-02-2	159	402	0.2651	0.710249	0.000006	2.21	16.0	0.0857	0.511723	0.000006	0.710139	−17.8	2346
WDS-02-4	160	425	0.2781	0.710146	0.000006	2.26	16.1	0.0959	0.511722	0.000005	0.710142	−17.8	2484
WDS-02-6	157	395	0.2976	0.710287	0.000007	2.34	17.1	0.0904	0.511733	0.000005	0.710263	−17.6	2604
WDS-02-8	155	401	0.2728	0.710223	0.000005	2.41	17.6	0.0965	0.511734	0.000005	0.710034	−17.6	2339
WDS-02-10	157	403	0.2911	0.710211	0.000007	2.26	17.7	0.0854	0.511730	0.000005	0.710092	−17.7	2346
WDS-03-2	128	623	0.2151	0.708634	0.000007	4.83	35.9	0.0867	0.511904	0.000005	0.708519	−14.3	2369
WDS-03-4	118	639	0.2103	0.708532	0.000006	5.32	39.5	0.0831	0.511904	0.000006	0.708425	−14.3	2266
WDS-03-6	125	588	0.2016	0.708673	0.000005	4.72	34.2	0.0867	0.511904	0.000005	0.708516	−14.3	2276
WDS-03-8	128	576	0.1612	0.708685	0.000007	4.58	33.6	0.0934	0.511900	0.000005	0.708527	−14.4	2634
WDS-03-10	130	616	0.1543	0.708535	0.000007	4.95	35.7	0.1014	0.511918	0.000005	0.708314	−14.0	2602

Note: constants used in calculation: $\lambda_{\text{Sm}} = 6.54 \times 10^{-12}$; $\lambda_{\text{Rb}} = 1.42 \times 10^{-11}$, depleted mantle (DM): $^{147}\text{Sm}/^{144}\text{Nd} = 0.2137$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.51315$. Initial $I_{\text{Sr}}(t)$ and $\epsilon_{\text{Nd}}(t)$ calculate with $t = 112 \text{ Ma}$.

Table 4. Zircon Hf isotopic characteristics of the Weideshan pluton.

Point Number	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	2σ	$\epsilon_{\text{Hf}}(0)$	$\epsilon_{\text{Hf}}(t)$	t_{DM1} (Ma)	t_{DM2} (Ma)	$f_{\text{Lu/Hf}}$
WDS-01-1-04	0.011920	0.000592	0.282266	0.000019	−17.8	−15.2	1375	2145	−0.98
WDS-01-1-09	0.014741	0.000710	0.282309	0.000018	−16.4	−13.6	1320	2050	−0.97
WDS-01-1-13	0.017387	0.000879	0.282266	0.000018	−17.9	−15.2	1387	2148	−0.97
WDS-01-1-19	0.013511	0.000661	0.282256	0.000020	−18.2	−15.5	1392	2168	−0.98
WDS-01-1-22	0.012917	0.000596	0.282313	0.000021	−16.2	−13.5	1311	2042	−0.98
WDS-02-1-03	0.013523	0.000609	0.282252	0.000017	−18.4	−15.6	1396	2178	−0.98
WDS-02-1-09	0.015089	0.000717	0.282268	0.000018	−17.8	−15.1	1378	2143	−0.97
WDS-02-1-15	0.011622	0.000537	0.282300	0.000020	−16.6	−13.9	1327	2069	−0.98
WDS-02-1-19	0.013977	0.000663	0.282287	0.000019	−17.1	−14.4	1349	2099	−0.98
WDS-02-1-23	0.017339	0.000805	0.282254	0.000020	−18.3	−15.6	1400	2174	−0.97
WDS-03-1-01	0.012773	0.000580	0.282294	0.000018	−16.8	−14.1	1336	2083	−0.98
WDS-03-1-09	0.010822	0.000483	0.282316	0.000018	−16.1	−13.3	1302	2033	−0.98
WDS-03-1-12	0.012642	0.000569	0.282291	0.000018	−16.9	−14.2	1340	2089	−0.98
WDS-03-1-19	0.013287	0.000655	0.282251	0.000018	−18.4	−15.7	1399	2181	−0.98
WDS-03-1-24	0.020256	0.000866	0.282332	0.000022	−15.5	−12.8	1294	1999	−0.97

Note: constants used in calculation: $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} = 0.0332$, $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR},0} = 0.282772$; $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}} = 0.0384$, $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM},0} = 0.28325$; constant $\lambda = 1.867 \times 10^{-11} \text{ a}^{-1}$.

4. Results

4.1. Zircon U-Pb Dating

We dated three samples of monzogranite from the Weideshan pluton (Table 1). The dated zircons of the three samples were mostly light gray in color, idiomorphic to short columnar in shape having length:width ratios ranging from 1:1.5 to 1:5, with smooth surfaces and oscillatory zoning (Figure 4), indicative of a magmatic origin. Some zircons had dark rims due to the effects of fluid activity after crystallization.

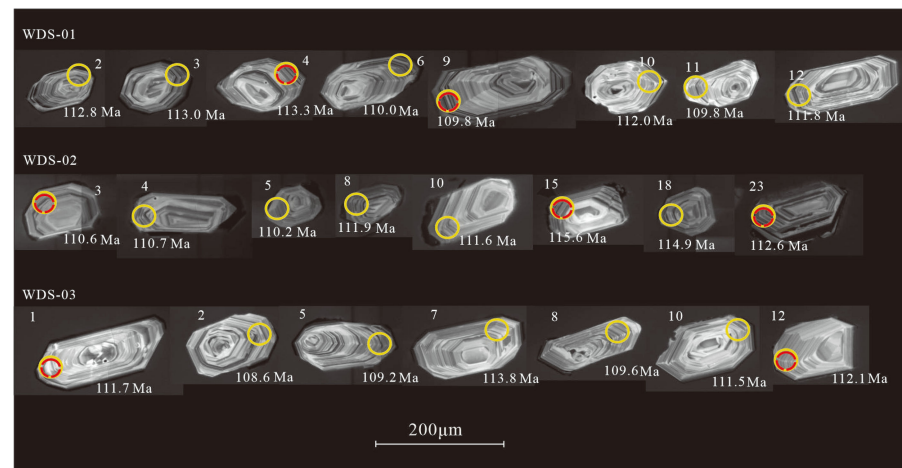


Figure 4. CL images of zircons from the Weideshan pluton. The yellow circle is the zircon U-Pb dating point, and the red circle is the Hf isotope analysis point.

Seventy-five spots were analyzed from three samples of the Weideshan pluton. The analyzed zircons had U = 175–950 ppm, Th = 175–990 ppm, with a Th/U ratio between 0.34 and 1.59, indicating that the zircons were of magmatic origin. The $^{206}\text{Pb}/^{238}\text{U}$ age values of each sample were similar and fell in a cluster close to the concordia curve. The weighted-mean $^{206}\text{Pb}/^{238}\text{U}$ ages were $112.83 \pm 0.80 \text{ Ma}$ (MSWD = 1.9) for sample WDS-01 ($n = 23$), $112.64 \pm 0.91 \text{ Ma}$ (MSWD = 1.8) for WDS-02 ($n = 17$), and $111.82 \pm 0.78 \text{ Ma}$ (MSWD = 1.6) for WDS03 ($n = 20$) (Figure 5).

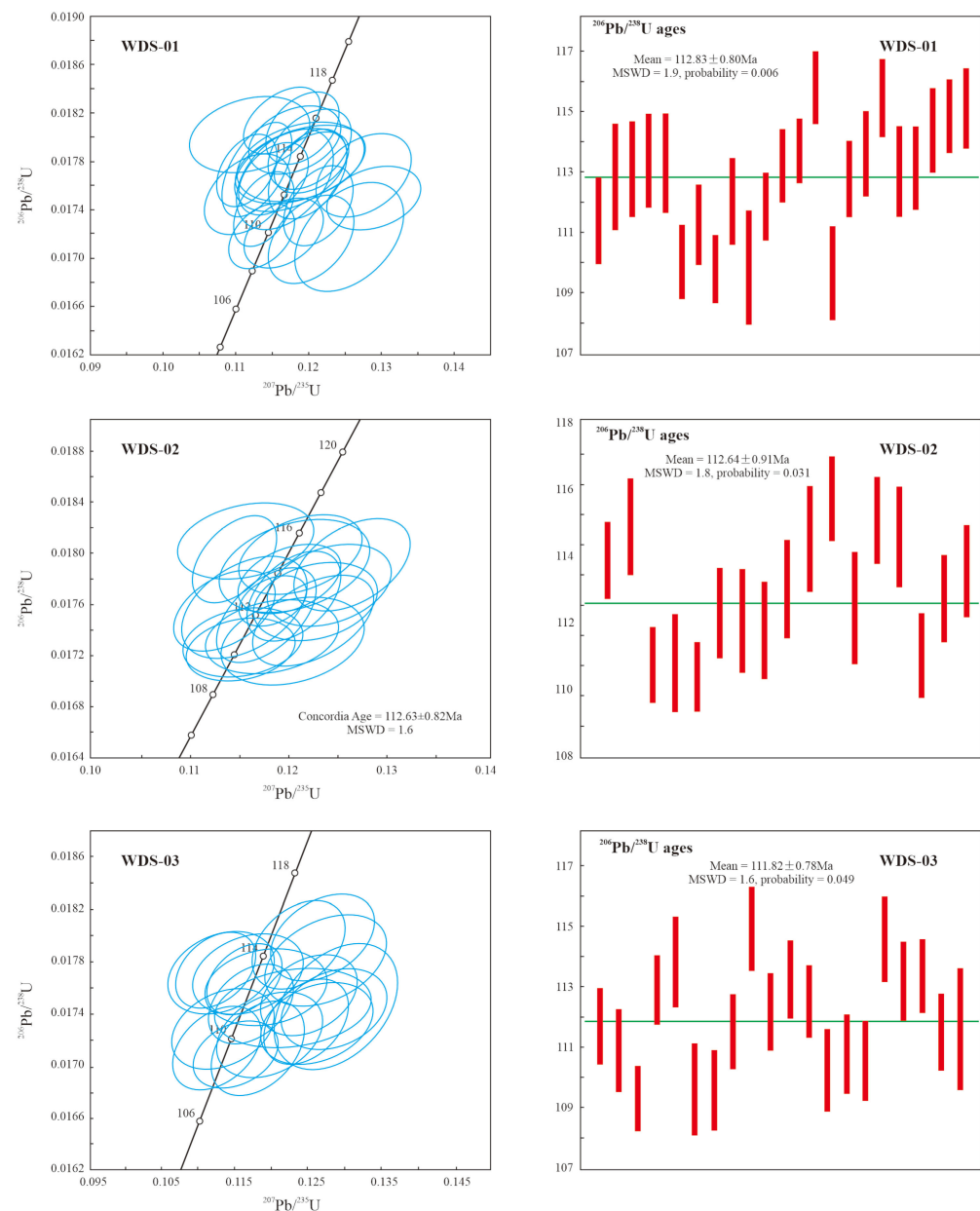


Figure 5. U-Pb Concordia and the weighted-mean age diagrams of zircons from the Weideshan pluton.

4.2. Major and Trace Elements

The results of the total rock major and trace element analysis of the Weideshan pluton samples (Table 2) showed that the SiO_2 contents of the porphyritic fine-grained monzogranite (WDS-01 and WDS-03) varied from 67.3 to 70.3 wt.%, with $\text{K}_2\text{O} + \text{Na}_2\text{O} = 7.8\text{--}8.8$ wt.% and $\text{K}_2\text{O}/\text{Na}_2\text{O} = 0.87\text{--}1.41$ (i.e., Na-rich). On the $\text{SiO}_2\text{--K}_2\text{O}$ diagram, the samples plotted in the high-K calc-alkaline field (Figure 6a) [51]. The Al_2O_3 contents were 14.5–15.0 wt.%, and the aluminum index (A/CNK) [$\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$] value was 0.88–0.92, similar to metaluminous I-type granites (Figure 6b) [52]. On the total alkalis-silica (TAS) classification diagram, the samples plotted in the quartz monzonite, granodiorite, and granite fields (Figure 7) [52].

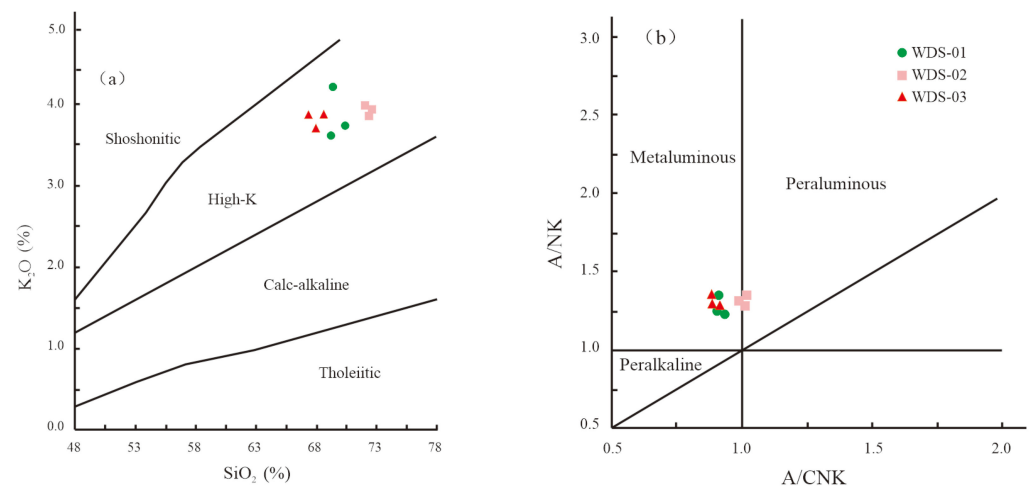


Figure 6. (a) K₂O-SiO₂ (after [51]) and (b) A/CNK-A/NK (after [52]) diagrams of the Weideshan pluton.

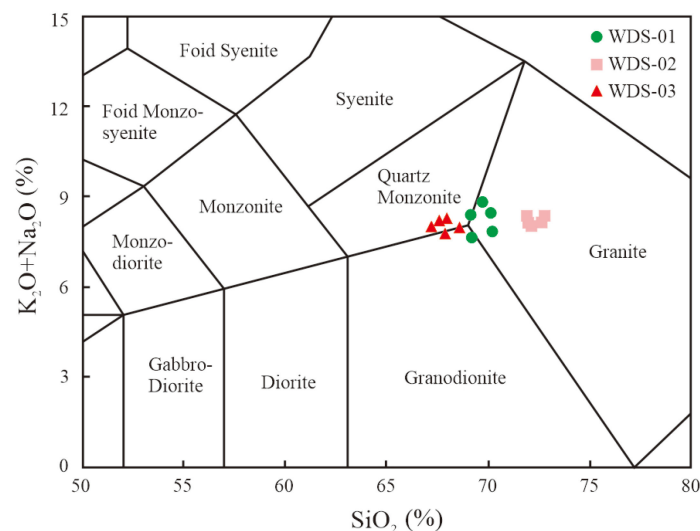


Figure 7. TAS diagram of the Weideshan pluton in Jiaodong (after [52]).

The SiO₂ contents of the porphyritic biotite-bearing monzogranite (WDS-02) varied from 72.1 to 72.7 wt.%, with K₂O + Na₂O = 8.2–8.3 wt.% and K₂O/Na₂O = 0.88–0.92 (i.e., Na-rich). The Al₂O₃ contents were 14.9–15.2 wt.%, and the A/CNK values were 0.99–1.01, straddling the metaluminous to peraluminous boundary but falling within the I-type granite field (A/CNK < 1.1) (Figure 6b). On the SiO₂-K₂O diagram, the samples plotted in the high-K field (Figure 6a). On the TAS diagram, the samples plotted in the granite fields (Figure 7).

It can be seen from the chondrite-normalized distribution diagram of rare earth elements (Figure 8a) that the curves for the Weideshan pluton samples were similar in shape, with the LREE part having a steep slope and the HREE part having a gentle slope. The (Eu/Eu*)_N values of the porphyritic fine-grained monzogranite (WDS-01 and WDS-03) were close to 1 (0.76–1.14), indicating little or no plagioclase fractionation. The (Eu/Eu*)_N values of the porphyritic biotite-bearing monzogranite (WDS-02) were slightly positive (1.19–1.29), suggesting minor plagioclase enrichment.

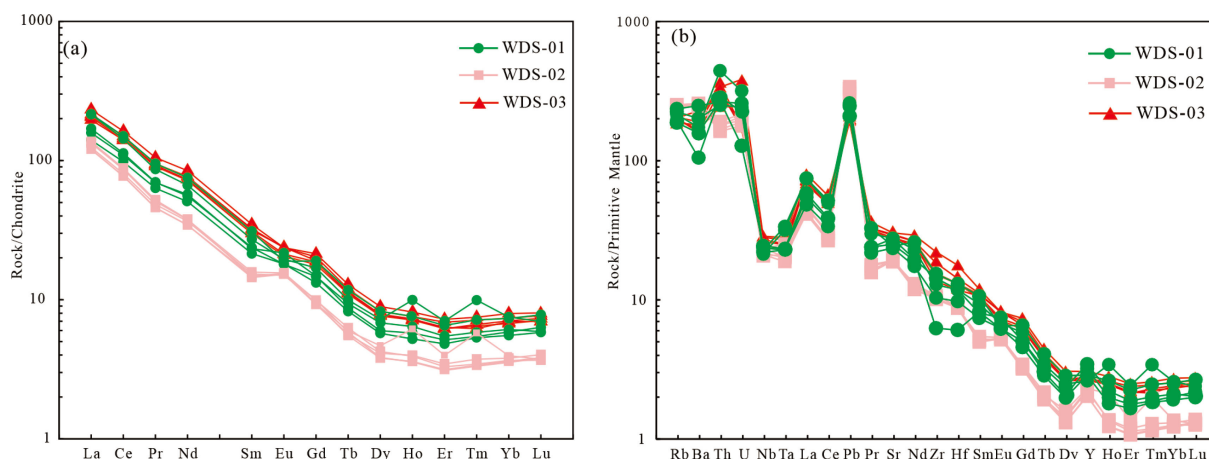


Figure 8. Chondrite-normalized rare earth element distribution patterns (a) and primitive mantle-normalized trace elements spider diagram (b) from the Weideshan pluton. (Chondrite-normalized data are from [53]).

As shown in the primitive mantle-normalized trace elements spider diagram (Figure 8b) [53], the Weideshan pluton was enriched in large-ion lithophile elements (Ba, Rb, and Sr) and relatively depleted in high-field-strength elements (Nb, Ta, Zr, and Hf), with marked positive Rb, Ba, Th, U, and Pb and negative Nb-Ta anomalies. The curves were similar for all samples (except the enclaves), indicating the same source rock characteristics and magmatic processes of different rock types. The total rare earth element (ΣREE) contents of the Weideshan granite were 104–221 ppm, and the LREE/HREE ratios were between 18.7 and 24.2 (Table 2). The slopes of the rare earth curves $(\text{La}/\text{Yb})_N$ ranged from 23.8 to 35.6, which highlighted the light to heavy REE fractionation (Figure 8b).

4.3. Strontium-Nd Isotopes

The Sr and Nd isotope data of the Weideshan pluton are listed in Table 3. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}(t)$ values calculated at 112 Ma could be divided into two groups, which may reflect that the magma source was not unique. The $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and $\varepsilon_{\text{Nd}}(t)$ of medium-grained monzogranite (WDS-01 and WDS-03) ranged from 0.708314 to 0.708762 and from -14.4 to -14.0 , respectively, while the $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and $\varepsilon_{\text{Nd}}(t)$ of porphyritic biotite-bearing monzogranite (WDS-02) ranged from 0.710034 to 0.710263 and from -17.8 to -17.6 , respectively, showing slightly higher $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and slightly lower $\varepsilon_{\text{Nd}}(t)$ for the biotite-bearing monzogranite than for the medium-grained monzogranite.

4.4. Zircon Hf Isotopes

Five dated zircons from each of the dated samples were analyzed for Hf isotopes (Table 4). The initial Hf isotope ratios and $\varepsilon_{\text{Hf}}(t)$ values were calculated at the measured $^{206}\text{Pb}/^{238}\text{U}$ ages for each individual spot. The $^{176}\text{Lu}/^{177}\text{Hf}$ ratios of all the measured spots were less than 0.001, indicating that the zircons had a low accumulation of radiogenic Hf after their formation. The initial $\varepsilon_{\text{Hf}}(t)$ values of sample WDS-01 ranged from -15.5 to -13.5 (mean = -14.6), with a two-stage model age (t_{DM2}) ranging from 2168 to 2042 Ma (mean = 2110 Ma). The initial $\varepsilon_{\text{Hf}}(t)$ values of sample WDS-02 ranged from -15.6 to -13.9 (mean = -14.9), with $t_{\text{DM2}} = 2178 - 2069$ Ma (mean = 2132 Ma). The initial $\varepsilon_{\text{Hf}}(t)$ values of sample WDS-03 ranged from -15.7 to -12.8 (mean = -14.0), and $t_{\text{DM2}} = 2181$ to 1999 Ma (mean = 2077 Ma).

5. Discussion

5.1. Age of the Weideshan Pluton

The zircon U-Pb ages of the three Weideshan pluton samples in this study were 112.83 ± 0.80 Ma, 112.64 ± 0.91 Ma, and 111.82 ± 0.78 Ma, which had good consistency.

Given that zircon has a high closure temperature and is resistant to resetting by later hydrothermal activity, the age results of this study of ~112 Ma should represent the crystallization age of the Weideshan pluton, which is in the late Early Cretaceous.

Previous studies of Weideshan granite in the Jiaodong area have obtained ages of 123–110 Ma, with a peak value of 120 Ma [26,27,32,40,54–56]. The crystallization ages of plutons in the Jiaobei area are Nansu (118.7 ± 0.9 Ma) [27], Ai Shan (118.0 ± 0.7 Ma) [9], and Yashan (117.7 ± 2.9 Ma) [27], and the ages of plutons in the Weihai uplift area are Zetou (115.6 ± 1.1 Ma) [26] and Weideshan (113.1 ± 1.1 Ma) [27] from west to east. The age of plutons is gradually decreasing from west to east, which indicates that the Weideshan pluton belongs to the late stage of the Weideshan granites.

5.2. Magma Source and Petrogenesis

The three pluton samples were associated with SiO_2 contents of 67.3 to 72.7 wt.% and K_2O concentrations between 3.6 and 5.2 wt.%, indicating that the samples were K-rich and belonged to the high-K calc-alkaline series. The A/CNK values were 0.88–1.01, indicative of metaluminous to slightly peraluminous I-type granites. The samples were enriched in light REEs and large-ion lithophile elements and relatively depleted Nb and Ta, which indicated that the magma sources were derived from crustal material or through metasomatism of residual subducted oceanic crust [57]. The zircon $\varepsilon_{\text{Hf}}(t)$ values of the Weideshan pluton were -12.8 to -15.7 (mean = -14.5) and plotted above the crustal evolution line of the North China Craton (Figure 9). The negative value indicated that the partial melting source area of granite could be the lower crust [26] or a mixture of mantle-derived magma and upper crust. The high initial $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios (0.708 to 0.710) were in the range of the lower North China crust, and the low $\varepsilon_{\text{Nd}}(t)$ values (-17.8 to -14.0) were higher than the range of the crust. In a $\varepsilon_{\text{Nd}}(t)$ – $^{87}\text{Sr}/^{86}\text{Sr}$ diagram (Figure 10) [58], the Weideshan pluton samples plotted above the lower North China crust and along a crust–mantle mixing line. The Sr–Nd isotopes of the Weishan pluton were similar to those of the Yashan pluton and the Zetou pluton, which was interpreted as the melting of ancient crust, possibly with a small amount of mixed mantle derived magma [40,59]. The model age (t_{DM2}) values of Hf isotope were 2180 to 2000 Ma (mean = 2110 Ma), which was consistent with the age of the Paleoproterozoic metamorphic rocks in the Jiaodong area [24,60]. Moreover, previous research shows that the two-stage model age (t_{DM2}) data are 2210 to 2740 Ma (Zetou pluton) [26], 1900 to 2300 Ma (Weideshan granites) [27], and 2090 to 2300 Ma (Sanfoshan pluton) [61]. These results indicate that the magma source of these granites is mainly composed of Paleoproterozoic to Neoarchean crustal material, and the differences in crustal material may indicate the crustal composition within different tectonic units. Therefore, it is considered that partial melting of the lower crust composed of early Precambrian metamorphic basement rocks in the Jiaodong was an important magma source for Weideshan pluton.

The porphyritic biotite-bearing monzogranite (WDS-02) showed slightly higher $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and slightly lower $\varepsilon_{\text{Nd}}(t)$ isotope values than the medium-grained monzogranites (WDS-01 and WDS-03), indicating that less mantle-derived material was involved in the diagenetic process of the porphyritic biotite-bearing monzogranite, and there may be magma mixing locally [28,61,62]. This was consistent with the fact that the Weideshan granites generally contained micro-diorite enclaves with mantle-derived geochemical characteristics [62–66]. Previous studies on Sr–Nd isotopic compositions of the enclaves showed that $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and $\varepsilon_{\text{Nd}}(t)$ values were 0.70787 to 0.71225 and -18.8 to -15.1 , respectively, similar to those of the host rocks, and the compositions of biotite and hornblende in the enclaves were basically consistent with those in the host rocks [38,64]. In addition, the zircon SHRIMP U–Pb age of enclaves in the Yashan pluton measured by Goss et al. [65] is 116 ± 1.0 Ma, which is similar to the age of the host rock (117.7 ± 2.9 Ma), indicating that enclaves and host rocks were formed at the same time. The overall data suggest that the Weideshan magma was mainly derived from older crust with a small amount of mantle material mixed in.

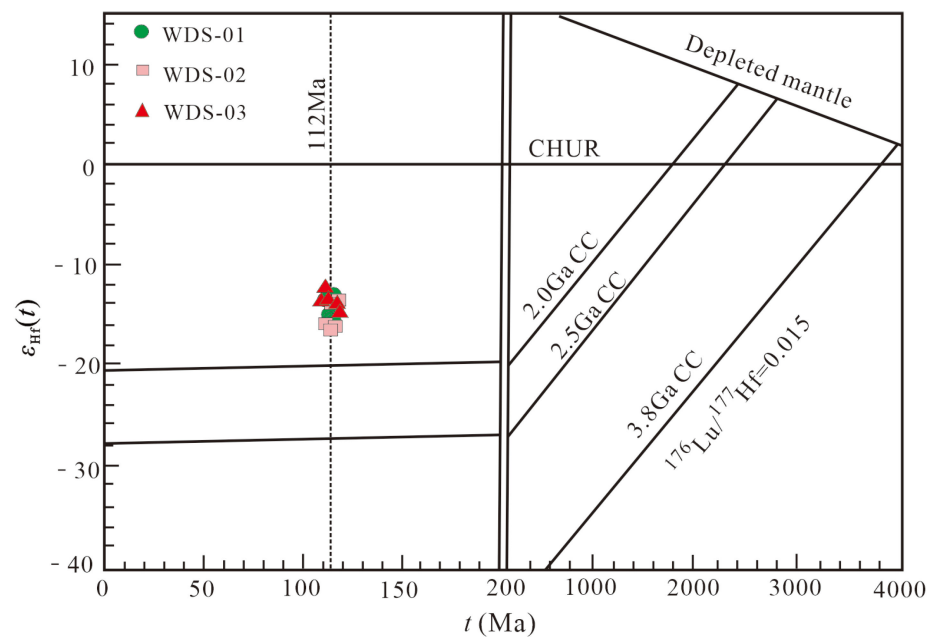


Figure 9. Zircon Hf isotopic compositions of the Weideshan pluton.

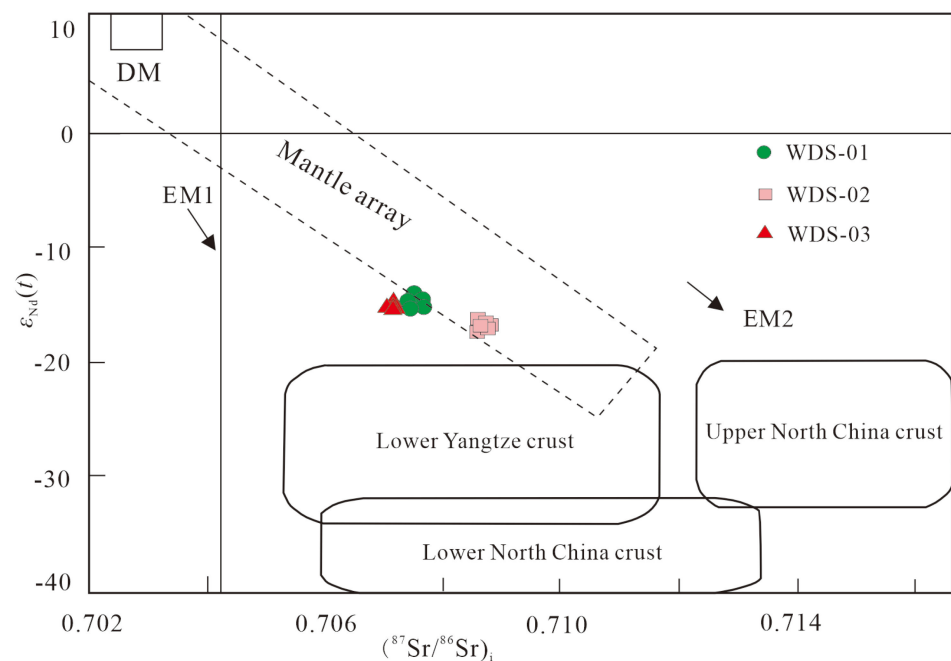


Figure 10. $\epsilon_{Nd}(t)$ – $(^{87}Sr/^{86}Sr)_i$ diagram for the Weideshan monzogranites (fields of Yangtze crust, upper and lower crust in the North China Craton from [58]).

On the Harker diagram (Figure 11), there is a good linear relationship between SiO_2 and most other major elements contents for all three sample groups. As SiO_2 increased, TiO_2 , MgO , CaO , Fe_2O_3 , and P_2O_5 contents decreased. K_2O and Na_2O showed a flat trend, while MnO was flat in WDS-01 and WDS-03 but lower in WDS-02. Al_2O_3 showed a decreasing trend for WDS-01 and WDS-03, while WDS-02 deviated. This indicated that the WDS-01 and WDS-03 samples probably were co-magmatic, while the WDS-02 samples had a deviating source. However, there was no obvious linear relationship between SiO_2 and major element contents of porphyrite-bearing monzogranite (WDS-02).

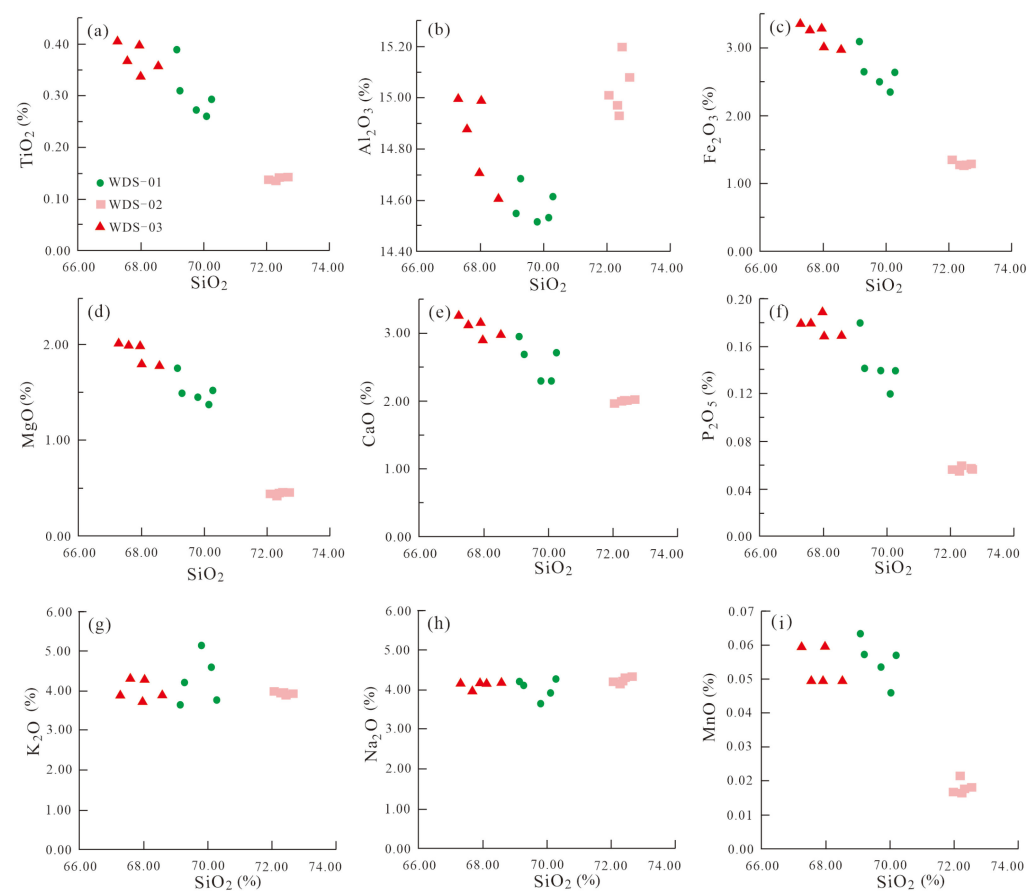


Figure 11. Diagrams of major elements (Ti (a), Al (b), Fe (c), Mg (d), Ca (e), P (f), K (g), Na (h), Mn (i)) versus SiO_2 of the Weideshan pluton.

The Weideshan pluton had high Sr (402 to 639 ppm) and Ba (736 to 1801 ppm) content and low Rb/Sr (0.18 to 0.40) and medium-high K/Rb (0.20 to 0.28) ratios. These geochemical characteristics indicated that there was unlikely to be a large amount of separation and crystallization of feldspar and mica during fractionation. The porphyritic medium-grained monzogranite had little or no Eu anomaly and a low Sr/Y ratio, indicating little or no plagioclase fractionation.

5.3. Tectonic Setting

The elements Y, Nb, Ta, and Yb can distinguish granites formed in different tectonic settings. The Weideshan pluton plotted in the volcanic arc granite field in these diagrams, straddling the syn-collision granite field in Figure 12b (Figure 12) [67]. Studies have shown that high Ba and Sr granites were usually formed in tensional or non-compressional tectonic settings [68–70]. On the Ta/Yb-Th/Yb diagram, the samples plotted in the active continental margin field (Figure 13) [71], indicating that the tectonic setting for the formation of the Weideshan pluton was an active continental margin, closely linked with the westward subduction of the Paleo-Pacific Plate.

Numerous studies have shown that the North China Craton was in an extensional setting during the late Paleozoic and underwent large-scale lithospheric thinning accompanied by intense magmatism [2–4,72–75]. The Cretaceous (130–110 Ma) was a time of important plate tectonic transformation in the North China Craton [76]. During the Early Cretaceous, large-scale tectonism, magmatism, mineralization, and basin subsidence occurred in the Jiaodong area, North China Craton, such as the formation of NNE trending fault systems, as well as the formation of the Jiaolai basin, granitoids, volcanic rocks, and intermediate-basic dykes, which were indicative of lithospheric extension during the peak of destruction of the North China Craton. The zircon U-Pb ages showed that the Weideshan

granite was formed in this tectonic settings. Many different models have been put forward by different scholars on the dynamic mechanism of the rapid thinning of the North China Craton, but the subduction and roll-back of the Paleo-Pacific plate are considered as the main driving forces of lithospheric thinning at this stage [28,72,77].

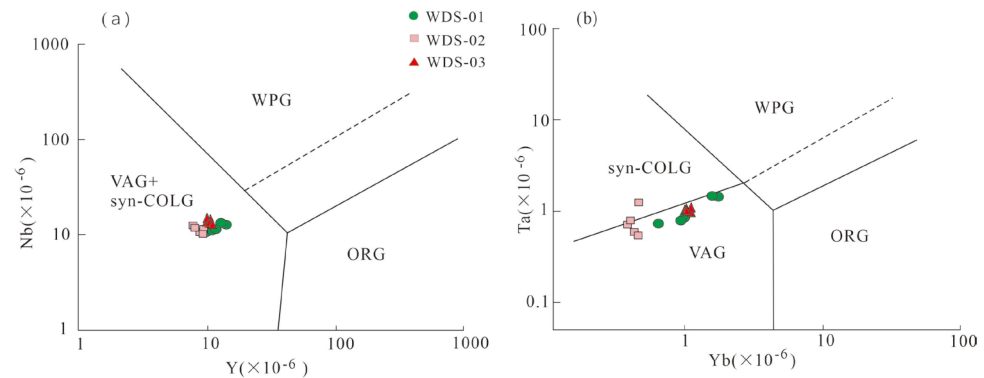


Figure 12. Nb–Y (a) and Ta–Yb (b) discrimination diagrams of the Weideshan pluton. (VAG—volcanic-arc granite; Syn-COLG—syn-collision granite; WPG—within-plate granite; ORG—ocean ridge granite. The dashed line arises from the boundary line for abnormal ORG (after [67]).

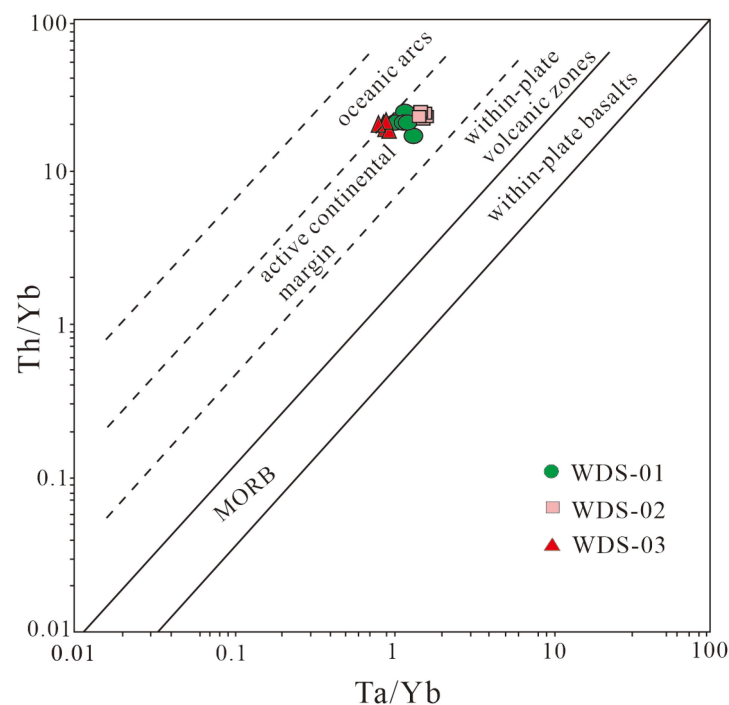


Figure 13. Plot of Ta/Yb–Th/Yb for the Weideshan pluton (after [71]).

At ca. 130 Ma, the subduction direction of the Paleo-Pacific Plate changed, and it then began to roll back [72,76]. This process resulted in strong tectonism and regional deformation in the eastern North China Craton and eventually led to the thinning and melting of the lithospheric mantle and upwelling of asthenospheric mantle [78]. This provided favorable conditions for voluminous magmatism. In the Jiaodong area, ascending mantle-derived magmas formed high-Mg diorites and mafic dikes, and the mixing and subsequent fractional crystallization of mantle-derived and crust-derived magmas formed the Weideshan granites (Figure 14) [40,61].

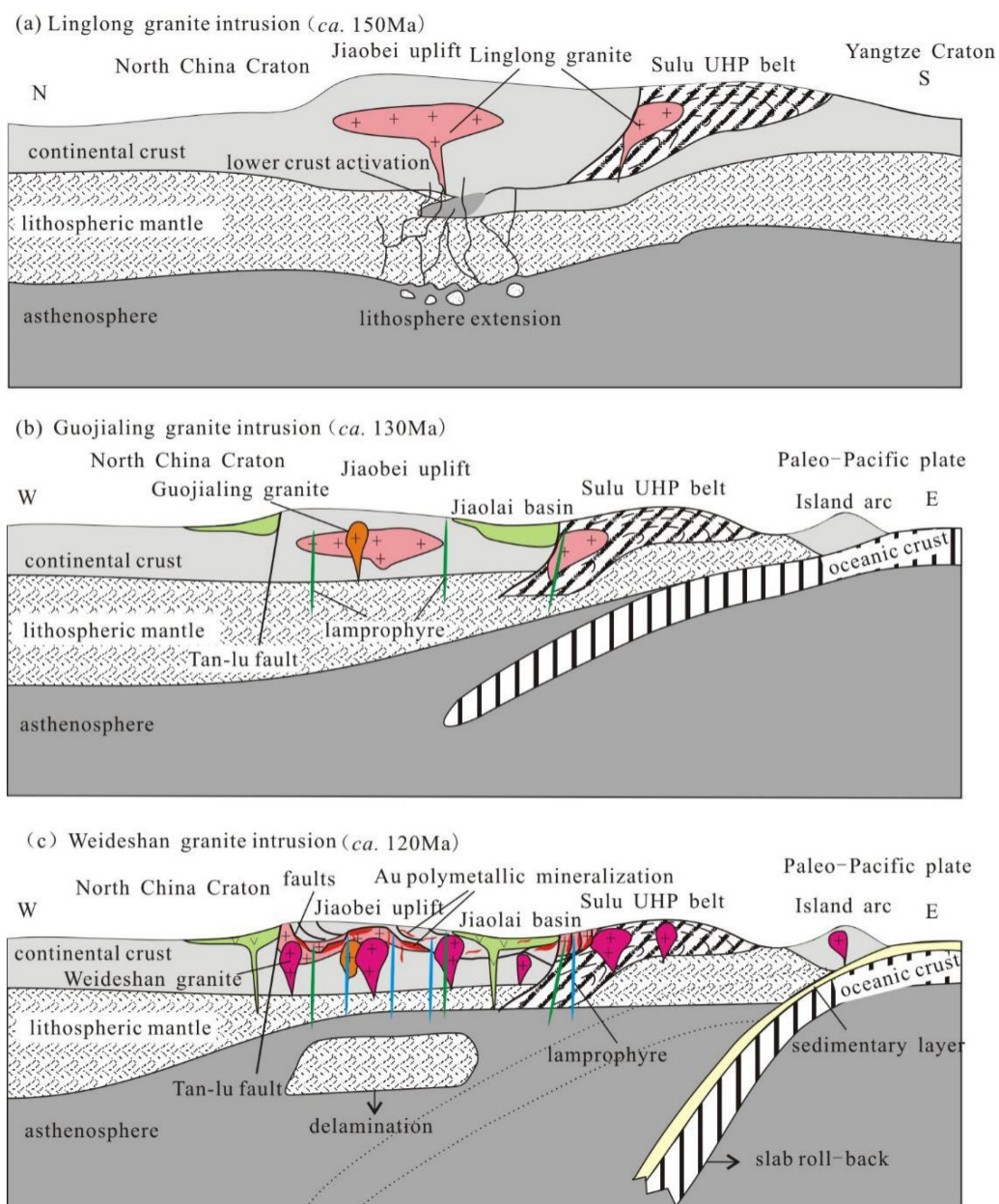


Figure 14. Geodynamic mechanism of Late Mesozoic magmatic activity in Jiaodong.

5.4. Relationship between Weideshan Granite and Gold Polymetallic Mineralization in Jiaodong

Previous studies have obtained numerous ages of Au mineralization by using different dating methods in the Jiaodong area, for example, ^{40}Ar - ^{39}Ar and K-Ar ages of sericite and quartz, U-Pb ages of hydrothermal zircons, Rb-Sr ages of pyrite, Re-Os ages of molybdenite, and Rb-Sr ages of fluid inclusions [17,18,30,40,79–82]. These data indicated that most Au deposits formed at ca. 115–125 Ma. Previous studies on the metallogenic age of Cu-Mo-Pb-Zn deposits in Jiaodong showed that the mineralization ages were concentrated at 120–110 Ma [24,25,33,83], similar to the mineralization age of the Jiaodong Au deposits. The formation age of the Weideshan pluton obtained in this study was 112 Ma, which was consistent with the previous research results (123–110 Ma) of Weideshan granites [26,27,32,40,54–56]. This showed that large-scale magmatism and mineralization occurred in the Jiaodong area at the same time and highlighted that the Au and Cu-Mo-Pb-Zn polymetallic mineralization in the Jiaodong area was associated with the Weideshan granites.

Regionally, Weideshan granite outcropped sporadically in the northwestern Jiaodong area in the form of small rock masses and dikes. In the eastern Jiaodong region, it outcropped as larger massifs. The crystallization ages of the Weideshan granites gradually decreased from west to east. The mineralization ages of the gold and polymetallic deposits from west to east were the Cangshang Au deposit (121.3 ± 0.2 Ma), the Sanshandao Au deposit (121.0 ± 2.0 Ma), the Jiaojia Au deposit (120.5 ± 0.6 Ma), the Linglong Au deposit (120.6 ± 0.9 Ma) [9], the Fanjiabu Au deposit (118.8 ± 0.6 Ma) [35], the Pengjiakuang Au deposit (117.5 ± 0.3 Ma) [9], the Rushan Au deposit (117.0 ± 3.0 Ma) [9], and the Shangjiazhuang Mo deposit (116.4 ± 1.6 Ma) [33] (Figure 1b). Comparing the diagenetic and mineralization ages in the Jiaodong area, it was found that there was a certain age difference between the gold and polymetallic mineralization age and the pluton's crystallization age in the same area. Generally, the crystallization age was 2–3 myr later than the mineralization age, and this age difference was basically consistent within the range of age error. The gold and polymetallic mineralization ages and the crystallization ages of the Weideshan granites showed the same variation characteristics from west to east, indicating that they were spatially synchronized.

The exploration practice showed that the locations of different gold and polymetallic deposits in eastern Jiaodong were consistent with the occurrence of Weideshan granites, that is, there were many polymetallic deposits with Cu, Mo, Pb, and Zn in or surrounding the Weideshan granites. The Dalijia Mo deposit in Rongcheng was hosted by granite porphyry of the Weideshan sequence; the Xiawolong Au deposit in Wendeng was located in porphyry amphibole monzonite of the Weideshan sequence; the Chenjiabu Cu deposit was located in the contact zone between the Weideshan pluton, Jingshan group marble, and the Rongcheng sequence; the Jinjiao Pb–Zn deposit in Rongcheng was located in the Qingshan group outside of the Weideshan granites; and the Huangbutun Au deposit in Weihai was located in the Rongcheng sequence outside of the Weideshan granites. It can be seen from the above that these ore deposits occurred in the inner part of the Weideshan granitic intrusion, along its contacts with surrounding rocks, and in country rocks proximal to the granite. There were porphyry-type deposits in the granite, skarn deposits at the contacts with surrounding rocks, and hydrothermal vein deposits in the country rocks. The Mo(W)–Cu–Pb(Zn)–Au (Ag) polymetallic deposits formed from the inner to outer parts of the Weideshan granites [25,31] and were genetically related to the granitic intrusions.

Previous studies have found that the ore-forming fluids in the Jiaodong gold deposits are of mesothermal, middle- to low-salinity H_2O – CO_2 – NaCl types [84]. $\delta\text{D}_{\text{V-SMOW}}$ varies from -83‰ to -117‰ , while $\delta^{18}\text{O}_{\text{V-SMOW}}$ ranges from 12.0‰ to 16.3‰ , suggesting that the ore fluids originated from magmatic water and subsequently mixed with a large amount of atmospheric water [85]. Sulfur isotope studies (Figure 15) showed that the $\delta^{34}\text{S}$ values of the Jiaojia and Sanshandao Au deposits were $+8\text{‰}$ to $+12\text{‰}$ and $+11\text{‰}$ to $+13\text{‰}$, respectively, and the $\delta^{34}\text{S}$ values of the Linglong Au deposit were $+5\text{‰}$ to $+9\text{‰}$ [86]. The $\delta^{34}\text{S}$ values of the Xiangkuang Pb–Zn–Cu deposit were -1‰ to $+5\text{‰}$ [87], that of the Shangjiazhuang Mo deposit was $+4.5\text{‰}$, and that of the Dadengge polymetallic deposit was $+7.0\text{‰}$ [88]. The sulfur of the Au and polymetallic deposits in Jiaodong showed similar sulfur isotope values to those of the ancient metamorphic basement rocks ($+7\text{‰}$ – $+10\text{‰}$), Mesozoic granites ($+3\text{‰}$ – $+15\text{‰}$), and mafic dikes ($+1\text{‰}$ – $+8\text{‰}$) in the Jiaodong area [80,89], indicating that the sulfur was most likely derived from the surrounding country rocks. Gold and polymetallic deposits with higher $\delta^{34}\text{S}$ values may reflect more sulfur isotope exchange with surrounding rocks during mineralization [89]. In addition, the initial Sr isotope values of gold ore, alteration minerals, and pyrite in the Jiaodong area were mainly greater than 0.710 (0.710–0.713), while some were between 0.708 and 0.710, which was consistent with the Weideshan granites. This indicated that the ore-forming materials were mainly crust-derived, with a small amount of mantle-derived components. These isotope characteristics indicated that the fluid circulation induced by the emplacement of the Weideshan granites may be the main source of ore-forming materials of the Au and polymetallic deposits.

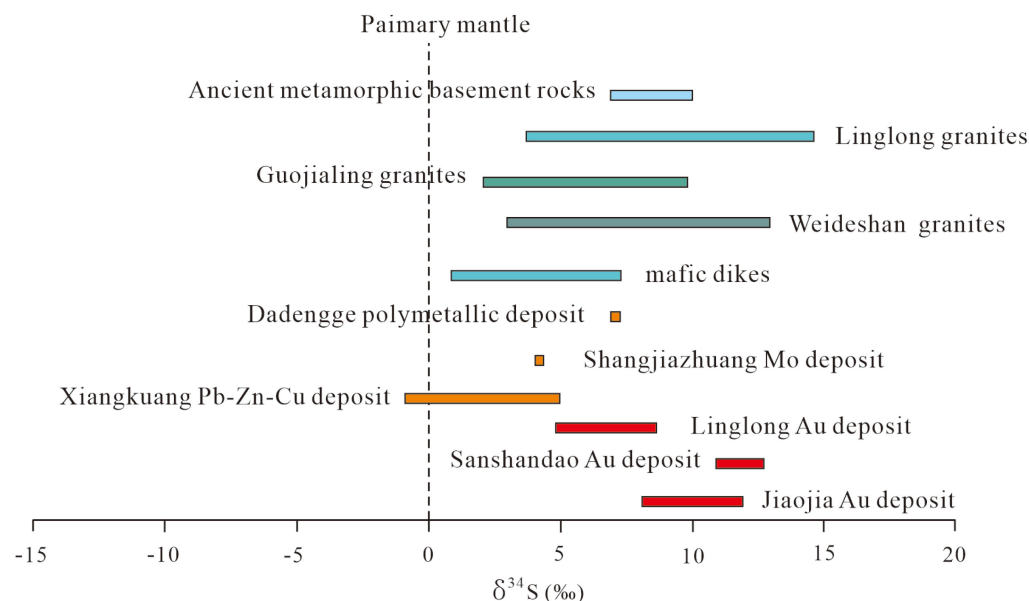


Figure 15. Sulfur isotope compositions of ores and the country rocks in the Jiaodong area (source of data: [80,86–89]).

The late Jurassic–early Cretaceous was a period of large-scale magmatism in Jiaodong. In the late Jurassic (ca. 150 Ma), the mantle began to rise, the lithosphere became thinner, the continental crust was remelted on a large scale, and the Linglong granite magma intruded, at a depth of about 10–15 km [38]. After magma consolidation and crystallization, it slowly rose with the tectonic activity. In the early Cretaceous (ca. 130 Ma), craton failure, lithosphere thinning, and asthenosphere upwelling occurred; Guojialing granite magma intruded, at a depth of about 13 km [90]; and mantle-derived basic dikes were also generated. In the middle of the early Cretaceous (ca. 120 Ma), the Paleo-Pacific Plate rotated, the front end rolled back, the lithosphere collapsed, and the Weideshan granites, the Laoshan granite, and intermediate–basic dykes intruded, with an emplacement depth of Weideshan granites of about 3 km [38,90]. The strong magmatism induced fluid circulation, and with the rapid uplift of the crust, the fluid boiled due to decompression, resulting in large-scale gold-polymetallic mineralization [18,72,91]. The metallic elements in the fluids were exsolved from the magma and precipitated in the granite and at or near its external contacts to form porphyry and skarn-type Mo, Mo-W, and Pb-Zn deposits. Fluid circulation in the surrounding country rocks extracted metals from the granite and surrounding rocks (i.e., mainly the Jurassic Linglong granite and Precambrian metamorphic rocks), which were then precipitated in the country rocks and formed vein-type polymetallic deposits and altered-rock- and vein-type Au deposits. After that, with the slow uplift and denudation of the crust, granite and some gold and polymetallic deposits were exposed at the surface.

6. Conclusions

1. LA-ICP-MS zircon U-Pb dating of three samples of the Weideshan pluton yielded Early Cretaceous ages of 112.83 ± 0.80 Ma, 112.64 ± 0.91 Ma, and 111.82 ± 0.78 Ma. These ages were consistent with those obtained in previous studies (126–108 Ma).
2. The initial $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios and $\epsilon_{\text{Nd}}(t)$ values ranged from 0.70853 to 0.71029 and from -18 to -14 . The values of $\epsilon_{\text{Hf}}(t)$ were between -13 and -16 . The ages of the second-stage model (t_{DM2}) were between 2000 and 2180 Ma. All these characteristics showed that the source of the Weideshan pluton magma was mixed, consisting mainly of crustal-derived material and a small amount of mantle-derived material.
3. The Weideshan pluton had high Ba and Sr, and plots of Nb-Y, Ta-Yb, and Sr/Y-Y showed it had the geochemical characteristics of continental arc granite and formed in tensional or non-compressional tectonic settings. The formation of the Weideshan

pluton may have been the effect of the subduction and roll-back of the Paleo-Pacific plate and the destruction of the North China Craton.

4. The crystallization ages of the Weideshan granites were consistent with the mineralization ages of gold and polymetallic deposits such as copper, molybdenum, lead, and zinc (123–110 Ma), and they were also spatially related. The Weideshan granite emplacement was the fundamental cause of the mineralizing fluid activities and provided the ore-forming materials, heat source, and fluids for the formation of gold and polymetallic deposits.
5. In this study, we used geochemistry and isotope data to constrain the petrogenesis of the Weideshan granite and its relationship to gold and polymetallic mineralization. Meanwhile, the results obtained in this study have certain guiding significance for gold and polymetallic exploration and prospecting practice. The interior of the Weideshan granites is favorable for Mo deposit prospecting; the contact zone with surrounding rocks is favorable for Pb, Zn, Cu, and Ag prospecting; and the periphery is favorable for Au (Ag) prospecting.

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