

Article

Late Early Jurassic Continental Arc Magmatism in the Northern Erguna Block: Implications for the Southward Subduction of the Mongol–Okhotsk Ocean

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Abstract

Late Early Jurassic continental arc magmatism in the northern Greater Khingan Range enables the investigation of complicated tectonic processes associated with the subduction and closure of the Mongol–Okhotsk Ocean. To further clarify the timing, genesis, and geodynamic mechanisms driving the magmatic activity during this period, the present study addresses these critical questions by integrating zircon U–Pb geochronological, geochemical, and isotopic analyses of a wide variety of igneous rocks, including gabbro, gabbro-diorite, granodiorite, porphyritic monzogranite, and biotite-bearing monzogranite from the Fushan region. Zircon U–Pb geochronology constrains the timing of magmatic activity to 184–179 Ma, coinciding with active subduction phases. Geochemical data reveal arc-like signatures characterized by enrichment in light rare-earth elements (LREEs) and large-ion lithophile elements (LILEs), together with pronounced depletion in high field strength elements (HFSEs). A comprehensive analysis of geochemical and Sr–Nd–Hf isotopic signatures suggests that the mafic rocks originated from an enriched lithospheric mantle modified by subduction-related fluids and sediment-derived melts. By contrast, the granodiorite and porphyritic monzonite exhibit adakitic characteristics, indicating partial melting of the thickened Mesoproterozoic lower crust with contributions from mantle-derived or newly formed crustal material. The biotite-bearing monzogranite, with its pronounced Eu anomaly and lower zircon saturation temperatures, reflects advanced magmatic differentiation from a shallower source. These findings indicate extensive crust–mantle interactions during the southward subduction of the Mongol–Okhotsk Ocean, driven by high-angle subduction and slab rollback.

Keywords: Mongol–Okhotsk Ocean; late Early Jurassic magmatism; zircon U–Pb geochronology; whole-rock geochemistry; crust–mantle interaction; continental arc magmatism



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1. Introduction

The Central Asian Orogenic Belt (CAOB) is one of the largest and longest-lived accretionary orogens on Earth, and its tectonic evolution has been the subject of numerous international syntheses [1,2]. The ancient Pacific Ocean and the Mongol–Okhotsk crustal system played significant roles in shaping the formation and evolution of the CAOB. This

influence extended to the Mesozoic tectonic evolution and geodynamic processes of the Greater Xing'an Range. Additionally, the system affected the Mesozoic crustal evolution of eastern Russia, central Mongolia, and northeastern China, while also contributing to the formation of numerous large and medium-sized mineral deposits [3–9]. Clarifying the ancient Pacific Ocean and the Mongol–Okhotsk crustal system is integral to unraveling the geological complexities of the CAO [7,10–12]. It is also crucial for the genesis analysis and prospecting work of mineral deposits in the region. Since the Devonian, the Mongol–Okhotsk Ocean (MOO) has subducted northward beneath the southern margin of the Siberian continental shelf [13–15]. This process evolved into bidirectional subduction during the Carboniferous [7,11,16,17]. Subsequently, its closure followed a distinctive “scissor-like” pattern, progressing from west to east and culminating in the formation of the Mongol–Okhotsk Suture Zone, which extends from central Mongolia to the Russian Far East [18–21].

Despite extensive research and pioneering plate tectonic frameworks established for the MOO [22–26], the tectonic evolution of MOO, especially its subduction mode and closure time, has always been a subject of controversy. In terms of subduction model, it has been suggested that the southward subduction experienced a transition from low-angle to high-angle subduction during the Early to Late Triassic [3,27]. Alternative models propose either persistent low-angle [4] or flat subduction during the Early Jurassic [6]. Northward subduction models, supported by tomographic imaging of slab remnants beneath Siberia [18,19] and paleomagnetic constraints from the Siberian margin [28], imply that the MOO was consumed primarily beneath the Siberian continent. Bidirectional subduction has also been proposed based on the symmetrical distribution of accretionary complexes and magmatic arcs on both sides of the suture zone [7,11,16,17], but the timing and duration of opposing subduction polarity remain poorly constrained. Thus, despite multiple lines of evidence, the subduction polarity of the MOO remains vigorously debated, and each model carries its own strengths and limitations. In terms of closure time, some scholars propose synchronous closure of the eastern and western segments in the Late Jurassic to Early Cretaceous, influenced by bidirectional subduction or the unique morphology of the continental margin [29]. Some scholars consider that the scissor-type closure pattern suggests that the western segment closed earlier [24,30], during the Late Triassic. By contrast, closure of the eastern segment has been attributed to the Early to Middle Jurassic [30] or Late Jurassic to Early Cretaceous [31,32]. However, the tectonic affinity of the Erguna block, a key component of the MOO system, remains debated. Recent paleomagnetic data suggest that the Erguna block may have been proximal to Siberia as early as the Ediacaran–Early Cambrian (~560–525 Ma), challenging the traditional view that it was part of the Amuria microcontinent. This has significant implications for understanding the early opening and subsequent evolution of the MOO [33].

Mafic magmatic rocks are a feature of nearly all stages of the Wilson orogenic cycle within the realm of plate tectonics [34]. Their diverse volumetric, geometric, and compositional traits tend to reflect the thermal and compositional variations of potential mantle sources and hence attest to their contrasting behavior toward distinct tectonic triggers [34]. They are critical to understanding the thermal structure of subduction zones and material cycling in the mantle wedge [35]. In addition, continental magmatic arcs, such as those formed during the MOO's subduction, hold key information on crust–mantle interactions and crustal evolution [34,36]. The Fukeshan area in the Erguna block is located approximately 100 km south of the Mongol–Okhotsk suture zone and contains well-preserved Mesozoic mafic and granitic arc magmatic rocks, making it an ideal region to study subduction dynamics and related crustal processes. This study conducts a comprehensive investigation of representative mafic magmatic rocks and granite rocks in the Fukeshan area, including petrography, geochemistry, U–Pb isotopic chronology, Sr–Nd isotopes, and zircon Hf iso-

topes. The manuscript aims to further constrain the subduction mode and closure pattern of the MOO, provide new insights into its southward subduction and slab rollback processes during the Late Jurassic, and elucidate the petrogenesis and tectonic setting of the continental magmatic arc at the northern margin of the Erguna block.

2. Geological Setting

The Erguna block is located in the Greater Khingan Range, which is located in the eastern section of the Central Asian Orogenic Belt (CAOB), bounded by the Siberian Craton to the north, the North China Craton to the south, and the Pacific Plate to the east (Figure 1a). This region consists of several micro-continental blocks, including the Erguna block, Xing'an block, Songnen–Zhangguangcai Ridge block, Jiamusi block, and Xingkai block (Figure 1b). Over geological time (from the Proterozoic to the Cenozoic), the region underwent tectonic superposition and transformation influenced by the ancient Asian Ocean system, the Mongol–Okhotsk tectonic system, and the Pacific tectonic system [37–40]. During the contraction of rift basins and the ancient Asian Ocean basin, these blocks, including the Erguna block, converged along an active margin, forming a collision orogenic belt characterized by accretionary complex structures.

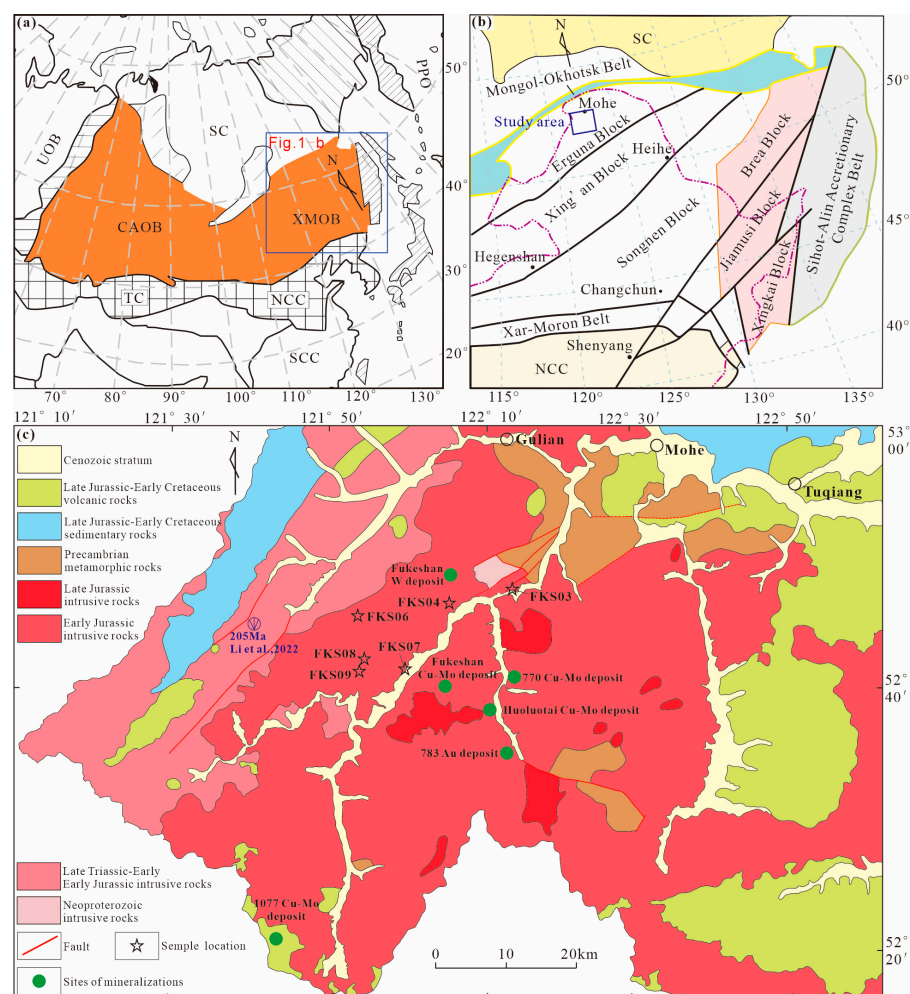


Figure 1. Geological sketch map of Fukeshan area. (a) Tectonic framework of the Central Asian Orogenic Belt, modified after ref. [41]; (b) Tectonic sketch map of Northeast China, modified after ref. [42]. (c) Simplified geological map of the Fukeshan area showing sample locations. UOB—Urra Orogenic Belt; CAOB—Central Asian Orogenic Belt; XMOB—Xing'an Mongolian Orogenic Belt; SC—Siberian Craton; TC—Tarim Craton; NCC—North China Craton; SCC—South China Craton; PPO—Paleo Pacific Ocean.

The study area is located at the northeastern margin of the Erguna block, close to the Mongol–Okhotsk suture zone (Figure 1b). This area encompasses strata spanning the Proterozoic, Mesozoic, and Cenozoic eras (Figure 1c), with structural controls predominantly oriented along a northeast (NE) trend. The Proterozoic strata are represented by the poorly exposed Neoproterozoic metamorphic complex of the Xinhua Dukuo group. Mesozoic strata include the Middle Jurassic clastic rock series of the Xiufeng Formation and the Late Jurassic continental volcanic formations. The Cenozoic is represented by Quaternary sediments.

Magmatic rocks are extensively distributed throughout the study area, exhibiting a predominant northeast (NE) orientation. Mesozoic intrusive rocks that serve as the research subjects are more extensive and typically form batholiths that intrude into older metamorphic complexes. The Mesozoic intrusive rocks can be categorized into three distinct stages: (1) Late Triassic Stage: Characterized by NE-trending intrusive belts dominated by gabbro, diorite, granodiorite, and (gneissic) syenogranite. Among them, gabbro and diorite are the products of co-genetic evolution under the background of the southward subduction of the Mongol–Okhotsk Ocean [43]. (2) Early–Middle Jurassic Stage: Features widespread intrusions into Late Triassic rocks, comprising medium- to coarse-grained monzogranite [4], along with gabbro, gabbro-diorite, granodiorite, porphyritic monzogranite, and biotite-bearing monzogranite (Figure 2). They intrude into Late Triassic intrusive rocks and neoproterozoic intrusive rocks (Figure 2). (3) Late Jurassic Stage: Features discontinuous NE-trending intrusions primarily consisting of quartz diorite porphyry, quartz monzonite, granodiorite porphyry, and syenogranite. These intrusions typically manifest as stock-like bodies emplaced within older geological units [4,6].



Figure 2. Cont.

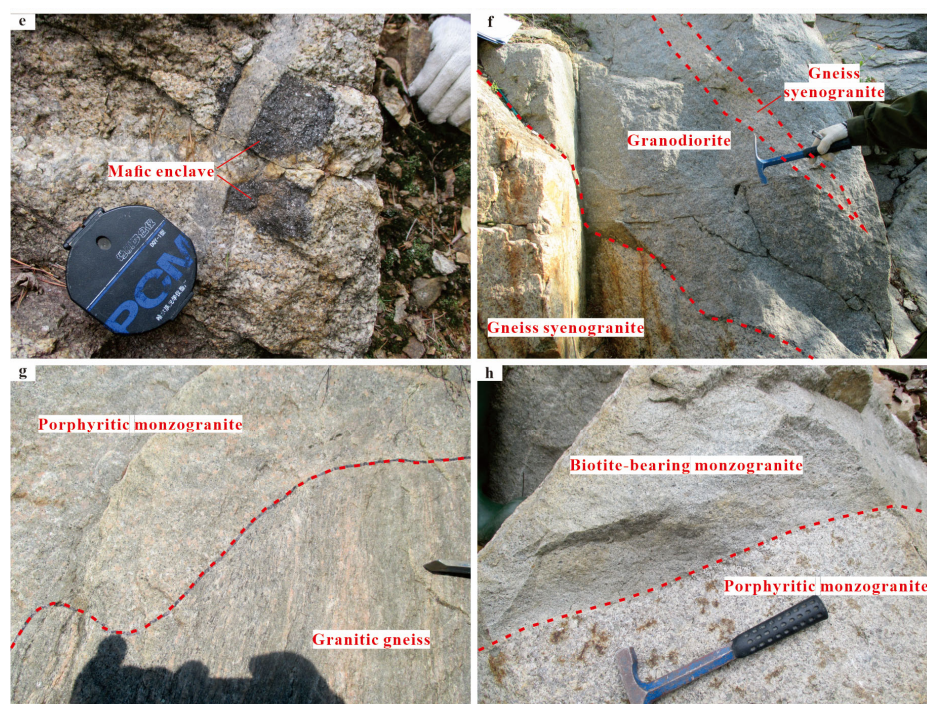


Figure 2. Typical field rock outcrops photos from intrusive rocks of Fukeshan area. (a) Field characteristics of gabbro (FKS06); (b) Field characteristics of granodiorite (FKS08); (c) Field characteristics of porphyritic granite (FKS03); (d) Field characteristics of biotite granite (FKS07); (e) mafic inclusions in granite diorite; (f) Late Jurassic granite diorite, intruding Late Triassic–Early Jurassic granulite; (g) Late Jurassic porphyritic monzogranite intruding Neoproterozoic granitic gneiss (FKS03); (h) Late Jurassic biotitic monzogranite in contact with porphyritic monzogranite. Dashed lines indicate lithological boundaries.

3. Petrography

This study focuses on the Early–Middle Jurassic intrusive rocks (stage2), for which representative samples include both mafic and granitic rocks from the study area, with a total of 13 samples collected (Figure 1c), including gabbro, gabbro-diorite, granodiorite, porphyritic monzogranite, and biotite-bearing monzogranite. The gabbro (FKS06) is a fine-grained gneissic rock (Figure 3a), comprising plagioclase (60%, 0.2–1.2 mm), hornblende (30%, 0.2–1.6 mm), pyroxene (8%, 0.2–2.0 mm), and biotite (2%, 0.1–0.5 mm). The microgranular granodiorite (FKS08) (Figure 3b) exhibits a medium-grained massive texture, dominated by microcline (20%, 0.8–5 mm), plagioclase (40%, 0.4–2.5 mm), quartz (25%, 0.3–3.8 mm), and biotite (15%, 0.4–1.3 mm). The porphyritic monzogranite (FKS03) (Figure 3c) features a porphyritic texture with alkali feldspar (40%, 0.2–6.0 mm), plagioclase (35%, 0.2–4.0 mm), quartz (23%, 0.15–1.6 mm), and accessory biotite (2%, 0.1–0.4). The biotite-bearing monzogranite (FKS07) (Figure 3d) is a medium-grained massive granite containing perthite (30%, 0.1–1.2 mm), plagioclase (25%, 0.15–2.5 mm), quartz (30%, 0.1–1.9 mm), biotite (13%, 0.2–2 mm), and minor garnet (2%, 0.3–2 mm). These samples provide critical insights into the magmatic processes and regional tectonic evolution during this key geological interval.

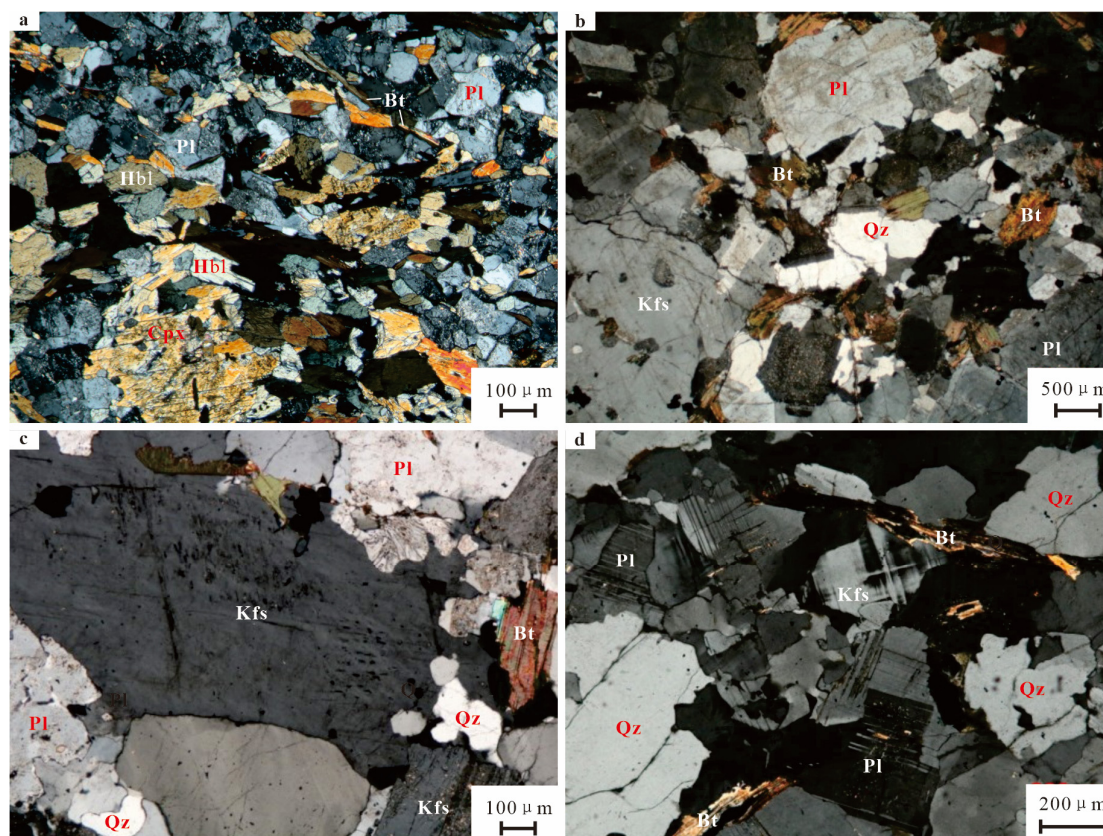


Figure 3. Typical photomicrographs of intrusive rocks from the Fukeshan area. (a) Gabbro (FKS06); (b) granodiorite (FKS08); (c) porphyritic monzogranite (FKS03); (d) biotitic granite (FKS07); Cpx—Clinopyroxene; Hbl—Hornblende; Kfs—Potash feldspar; Pl—Plagioclase; Bt—Biotite; Qz—Quartz.

4. Analytical Techniques

4.1. Zircon LA-ICP-MS U–Pb Analysis

Representative samples were analyzed at the Hebei Provincial Regional Geological Mineral Survey Institute, where zircon separation and cathodoluminescence (CL) imaging were conducted. U–Pb isotopic dating was carried out at Wuhan Sample Solution Analytical Technology Co., Ltd. (Wuhan, China), following the procedures outlined by ref. [44]. Analyses were performed using a GeolasPro laser ablation system (equipped with a COMPexPro 102 ArF 193 nm excimer laser, Coherent, Inc., Santa Clara, CA, USA) and a MicroLas optical system (Göttingen, Germany), coupled with an Agilent 7900 ICP-MS (Agilent Technologies, Santa Clara, CA, USA). The laser ablation utilized a 32 μm beam spot size with a frequency of 5 Hz. External standards for isotopic and trace element fractionation correction included zircon standard 91500 [45] and glass standard NIST610 [46]. Data acquisition involved time-resolved sequences of 20–30 s of blank signal collection followed by 50 s of sample signal collection. Offline data processing was conducted using ICPMS-DataCal software (version 11.4) for blank subtraction, drift correction, and calculations of element content, U–Pb isotopic ratios, and zircon ages. U–Pb concordia diagrams and weighted mean age calculations were generated using Isoplot/Ex_ver3 software (version 4.15) [47]. Analytical precision was verified using GJ-1 and Plesovice zircon standards, with the GJ-1 grains yielding a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 601.1 ± 1.1 Ma (2SD), consistent with the recommended values, and the Plesovice zircon grains producing a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 337.6 ± 0.71 Ma (2SD, $n = 16$), aligning with the recommended age of 337.13 ± 0.37 Ma (2SD). These results confirmed the reliability of the analytical methods

and provided a robust foundation for interpreting the U–Pb isotopic ages of the studied zircon samples.

4.2. Whole-Rock Sr–Nd Isotope Analyses

Whole-rock Sr–Nd isotope ratios were measured using a Neptune Plus MC-ICP-MS (Thermo Fisher Scientific, Bremen, Germany) at Wuhan Sample Solution Analytical Technology Co., Ltd. The experimental process involved analyzing seven samples between two Sr isotope standards [48] and seven samples between two Nd isotope standards [49]. All analytical data were processed using the professional isotope data processing software “Iso-Compass” (version 1.0) [50]. Repeated analysis for NBS-987 gave an average $^{87}\text{Sr}/^{86}\text{Sr} = 0.710244 \pm 0.000007$ ($n = 5$, 2SD). Repeated analysis for GSB gave an average $^{143}\text{Nd}/^{144}\text{Nd} = 0.512438 \pm 0.000009$ ($n = 9$, 2SD), which were in good agreement with the recommended $^{87}\text{Sr}/^{86}\text{Sr}$ age of 0.710248 and $^{143}\text{Nd}/^{144}\text{Nd}$ age of 0.512438.

4.3. Zircon Hf Isotopic Analysis

Hf isotope analyses were performed on selected zircon spots from samples FKS03, FKS07, and FKS08, which were previously dated for U–Pb isotopes. These analyses were conducted in situ at Wuhan Sample Solution Analytical Technology Co., Ltd. using a Geolas HD laser ablation system (Coherent, Inc., Santa Clara, CA, USA) coupled with a Neptune Plus MC-ICP-MS (Thermo Fisher Scientific, Bremen, Germany). Helium was used as the carrier gas, and nitrogen was introduced post-ablation to enhance sensitivity. A signal-smoothing device was employed to stabilize signals and improve isotope ratio precision. The laser spot size was fixed at 44 μm , with an energy density of approximately 10 J/cm². The GJ-1 zircon standard was used for external standardization and yielded a weighted mean value of 0.282003 ± 0.000013 (2σ , $n = 4$), which was in good agreement with the recommended $^{176}\text{Hf}/^{177}\text{Hf}$ age of 0.282009. For detailed instrument operating conditions and analytical methods, see ref. [51].

4.4. Major Oxides and Trace Elements Analysis

Whole-rock major and trace element analyses were performed at Wuhan Sample Solution Analytical Technology Co., Ltd. Fresh, unweathered samples were cleaned, dried, and ground to 200 mesh after coarse crushing. Major element compositions were determined using a ZSX Primus II wavelength dispersive X-ray fluorescence spectrometer (XRF) (Rigaku Corporation, Tokyo, Japan), with a relative standard deviation (RSD) below 2%. Trace element concentrations were analyzed using an Agilent 7700e ICP-MS (Agilent Technologies, Santa Clara, CA, USA), with an analytical precision of less than 10%.

5. Results

5.1. Zircon U–Pb Chronology

U–Pb geochronological analyses were conducted on 71 representative zircon grains extracted from late Early Jurassic gabbro, granodiorite, porphyritic monzogranite, and biotite-bearing monzogranite samples collected from the Fukeshan area (Table 1). The detailed analytical data and calculation results are summarized as follows.

Table 1. Zircon U–Pb data and ages.

Sample	Pb	Th ($\times 10^{-6}$)	U	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{235}\text{U}$		$^{206}\text{Pb}/^{238}\text{U}$		$^{207}\text{Pb}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{235}\text{U}$		$^{206}\text{Pb}/^{238}\text{U}$		Concordance
					Ratio	1 σ	Ratio	1 σ	Ratio	1 σ	Age (Ma)	1 σ	Age (Ma)	1 σ	Age (Ma)	1 σ	
FKS06 Gabbro																	
1	26.9	416.1	790.2	0.53	0.0462	0.0013	0.1808	0.0049	0.0283	0.0002	5.7	72.2	168.8	4.2	179.7	1.5	93%
3	33.6	731.5	935.1	0.78	0.0487	0.0013	0.1866	0.0048	0.0278	0.0002	131.6	64.8	173.7	4.1	176.7	1.4	98%
4	13.3	202.4	391.8	0.52	0.0539	0.0025	0.2028	0.0088	0.0274	0.0003	368.6	101.8	187.5	7.5	174.3	2.0	92%
5	10.8	133.6	319.2	0.42	0.0552	0.0023	0.2129	0.0088	0.0281	0.0003	420.4	100.9	196.0	7.3	178.5	1.8	90%
6	14.7	264.4	341.8	0.77	0.0474	0.0040	0.1829	0.0152	0.0277	0.0003	77.9	179.6	170.5	13.0	176.2	1.8	96%
7	24.3	393.2	705.0	0.56	0.0514	0.0015	0.2001	0.0057	0.0282	0.0003	257.5	66.7	185.2	4.8	179.4	1.7	96%
11	9.0	311.6	205.5	1.52	0.0552	0.0024	0.2179	0.0092	0.0287	0.0003	420.4	100.9	200.1	7.7	182.7	1.9	90%
12	16.5	528.8	389.8	1.36	0.0535	0.0016	0.2132	0.0063	0.0289	0.0002	350.1	66.7	196.3	5.3	183.4	1.6	93%
14	32.5	429.2	985.9	0.44	0.0467	0.0019	0.1747	0.0059	0.0282	0.0005	35.3	96.3	163.5	5.1	179.3	3.3	90%
16	5.8	131.8	146.3	0.90	0.0521	0.0025	0.2042	0.0101	0.0288	0.0004	287.1	109.2	188.6	8.5	182.8	2.3	93%
FKS08 Granodiorite																	
1	13.7	268.3	372.1	0.72	0.0489	0.0019	0.1935	0.0073	0.0288	0.0003	142.7	90.7	179.6	6.2	182.9	1.7	98%
2	17.2	365.6	472.1	0.77	0.0489	0.0017	0.1895	0.0063	0.0281	0.0003	142.7	79.6	176.2	5.4	178.7	1.6	98%
3	14.6	301.7	401.1	0.75	0.0490	0.0016	0.1884	0.0061	0.0279	0.0002	146.4	84.2	175.3	5.2	177.4	1.5	98%
4	20.1	501.7	512.2	0.98	0.0509	0.0016	0.1992	0.0061	0.0284	0.0003	235.3	70.4	184.5	5.2	180.2	1.7	97%
5	19.7	650.3	474.3	1.37	0.0512	0.0017	0.1967	0.0063	0.0278	0.0003	255.6	75.9	182.3	5.4	177.1	1.8	97%
6	10.8	186.2	302.5	0.62	0.0468	0.0016	0.1843	0.0064	0.0284	0.0003	39.0	77.8	171.8	5.5	180.7	2.0	94%
7	22.4	569.8	594.7	0.96	0.0480	0.0013	0.1829	0.0052	0.0275	0.0002	98.2	66.7	170.6	4.4	174.8	1.3	97%
8	18.2	444.8	489.0	0.91	0.0481	0.0017	0.1825	0.0062	0.0275	0.0002	105.6	83.3	170.2	5.3	174.9	1.4	97%
9	19.0	505.5	480.4	1.05	0.0463	0.0014	0.1802	0.0053	0.0282	0.0003	16.8	70.4	168.2	4.5	179.1	1.6	93%
10	17.7	487.6	453.2	1.08	0.0478	0.0016	0.1841	0.0061	0.0279	0.0003	87.1	79.6	171.5	5.2	177.6	1.7	96%
11	14.9	321.1	395.1	0.81	0.0482	0.0016	0.1891	0.0064	0.0284	0.0003	105.6	75.0	175.8	5.4	180.3	1.9	97%
12	21.1	519.7	559.5	0.93	0.0493	0.0016	0.1877	0.0055	0.0277	0.0003	166.8	74.1	174.7	4.7	176.2	1.7	99%
13	15.9	347.0	405.3	0.86	0.0508	0.0017	0.2003	0.0065	0.0286	0.0003	231.6	77.8	185.4	5.5	181.5	2.1	97%
14	19.2	414.9	494.9	0.84	0.0486	0.0014	0.1931	0.0053	0.0288	0.0003	131.6	68.5	179.3	4.6	183.3	1.8	97%
15	16.2	343.0	440.2	0.78	0.0497	0.0016	0.1928	0.0061	0.0281	0.0003	189.0	75.9	179.0	5.2	178.9	1.7	99%
16	25.5	743.2	630.0	1.18	0.0512	0.0013	0.1983	0.0053	0.0280	0.0003	255.6	59.2	183.7	4.5	178.1	1.7	96%
17	20.7	561.5	522.0	1.08	0.0539	0.0019	0.2081	0.0071	0.0280	0.0003	368.6	84.3	192.0	6.0	178.1	1.7	92%
18	16.1	389.5	410.8	0.95	0.0516	0.0016	0.2042	0.0065	0.0286	0.0003	333.4	75.0	188.7	5.5	181.9	1.8	96%
19	11.0	160.7	316.2	0.51	0.0522	0.0020	0.2042	0.0080	0.0285	0.0003	294.5	88.9	188.7	6.7	181.0	2.1	95%
FKS03 Porphyritic monzogranite																	
1	32.8	469.1	970.2	0.48	0.0522	0.0014	0.2107	0.0057	0.0293	0.0002	300.1	61.1	194.2	4.8	185.9	1.3	95%
2	11.9	132.5	367.7	0.36	0.0488	0.0017	0.1956	0.0068	0.0291	0.0003	139.0	81.5	181.4	5.8	185.0	1.9	95%
5	20.8	405.5	573.3	0.71	0.0514	0.0015	0.2077	0.0062	0.0293	0.0003	261.2	66.7	191.6	5.2	186.0	1.8	97%
7	20.3	216.3	614.9	0.35	0.0474	0.0015	0.1896	0.0059	0.0291	0.0003	77.9	61.1	176.3	5.0	184.6	1.7	95%
9	14.9	148.2	454.2	0.33	0.0493	0.0016	0.1957	0.0063	0.0289	0.0003	166.8	77.8	181.5	5.4	183.7	1.9	98%
10	22.8	330.6	677.5	0.49	0.0482	0.0014	0.1886	0.0055	0.0284	0.0002	105.6	70.4	175.4	4.7	180.8	1.5	97%
11	13.0	174.7	385.7	0.45	0.0486	0.0018	0.1951	0.0075	0.0291	0.0003	127.9	88.9	181.0	6.3	184.9	2.0	97%
12	27.8	459.9	795.1	0.58	0.0523	0.0013	0.2069	0.0053	0.0287	0.0002	301.9	62.0	191.0	4.4	182.1	1.3	95%
13	21.5	267.4	632.1	0.42	0.0514	0.0013	0.2056	0.0052	0.0290	0.0003	261.2	59.2	189.8	4.4	184.3	1.6	97%
14	8.7	131.3	251.7	0.52	0.0500	0.0020	0.1987	0.0081	0.0288	0.0003	194.5	94.4	184.0	6.9	183.2	2.1	99%
15	19.2	421.3	510.6	0.83	0.0525	0.0016	0.2092	0.0061	0.0288	0.0003	305.6	70.4	192.9	5.1	183.2	1.6	94%
16	18.8	424.5	505.1	0.84	0.0472	0.0016	0.1877	0.0066	0.0289	0.0003	57.5	81.5	174.7	5.7	183.6	2.0	95%
17	34.1	816.7	894.7	0.91	0.0506	0.0012	0.2014	0.0048	0.0289	0.0002	233.4	55.5	186.3	4.0	183.5	1.5	98%
18	19.2	396.3	520.4	0.76	0.0512	0.0015	0.2025	0.0060	0.0287	0.0003	250.1	63.9	187.2	5.1	182.4	1.7	97%
FKS07 Biotite-bearing monzogranite																	
1	8.6	79.7	265.1	0.30	0.0545	0.0024	0.2165	0.0097	0.0288	0.0004	390.8	100.0	199.0	8.1	183.3	2.7	91%
2	10.7	115.3	320.8	0.36	0.0502	0.0021	0.2001	0.0078	0.0290	0.0003	205.6	96.3	185.2	6.6	184.4	2.2	99%
3	17.1	360.9	486.7	0.74	0.0471	0.0015	0.1815	0.0057	0.0280	0.0003	53.8	74.1	169.4	4.9	178.0	1.6	95%
4	16.7	227.4	501.4	0.45	0.0510	0.0017	0.1988	0.0064	0.0283	0.0003	239.0	80.5	184.1	5.4	180.0	1.6	97%
5	15.6	188.8	462.5	0.41	0.0496	0.0016	0.1956	0.0062	0.0287	0.0004	176.0	78.7	181.4	5.2	182.2	2.4	99%
6	14.3	214.9	439.6	0.49	0.0534	0.0022	0.2038	0.0080	0.0277	0.0003	346.4	92.6	188.3	6.8	176.2	1.8	93%
7	8.8	128.0	257.1	0.50	0.0462	0.0019	0.1842	0.0073	0.0290	0.0003	5.7	96.3	171.7	6.3	184.4	2.1	92%
8	13.4	219.5	386.6	0.57	0.0495	0.0019	0.1914	0.0071	0.0282	0.0003	172.3	90.7	177.8	6.0	179.1	1.8	99%
9	12.2	164.7	365.2	0.45	0.0495	0.0020	0.1922	0.0077	0.0281	0.0003	172.3	94.4	178.5	6.6	178.7	1.8	99%
10	15.8	341.3	441.5	0.77	0.0466	0.0016	0.1793	0.0058	0.0279	0.0003	31.6	77.8	167.5	5.0	177.5	1.7	94%
11	12.5	337.4	326.4	1.03	0.0517	0.0021	0.1996	0.0083	0.0278	0.0003	272.3	86.1	184.8	7.0	176.8	1.7	95%
12	15.3	389.4	398.7	0.98	0.0518	0.0018	0.2017	0.0071	0.0281	0.0002	279.7	86.1	186.5	6.0	178.8	1.5	95%
13	15.1	348.3	406.0	0.86	0.0516	0.0019	0.1997	0.0072	0.0280	0.0003	333.4	80.5	184.9	6.1	178.2	1.7	96%
14	11.0	146.9	319.1	0.46	0.0486	0.0020	0.1929	0.0080	0.0287	0.0003	127.9	93.5	179.1	6.8	182.6	1.9	98%
15	14.2	275.4	386.0	0.71	0.0497	0.0020	0.1977	0.0078	0.0289	0.0003	189.0	125.0	183.2	6.6	183.8	2.2	99%
16	15.6	403.6	410.0	0.98	0.0498	0.0018	0.1929	0.0063	0.0281	0.0004	187.1	115.7	179.1	5.4	178.6	2.2	99%
17	17.6	490.3	444.3	1.10	0.0497	0.0018	0.1936	0.0066	0.0281	0.0003	189.0	83.3	179.7	5.6	178.9	1.9	99%
18	18.9	238.9	586.6	0.41	0.0467	0.0017	0.1820	0.0070	0.0281	0.0004	35.3						

5.1.1. Mafic Rocks

Gabbro (FKS06): Despite the rarity of zircon grains in the gabbro sample, extensive mineral separation efforts yielded only ~10 concordant spots suitable for age calculation. In cathodoluminescence (CL) images, the zircons from this sample exhibit long or short columnar shapes with axial ratios ranging from 5:1 to 1.2:1 and grain sizes of 100–180 µm. The zircons display clear rhythmic banding and core–mantle structures (Figure 4a). Among the 16 test points, the Th and U contents range from 416×10^{-6} to 876×10^{-6}

ten $^{206}\text{Pb}/^{238}\text{U}$ spots on ten zircon grains yield a weighted mean age of 179.2 ± 2.1 Ma (MSWD = 2.8), representing the rock's formation in the late Early Jurassic (Figure 5a). Six other zircons exhibit older $^{206}\text{Pb}/^{238}\text{U}$ ages of 221.9–212.4 Ma, 883.8–834.9 Ma, and 1203.7 Ma, associated with Late Triassic, Neoproterozoic, and Middle Mesoproterozoic magmatic activities, respectively.

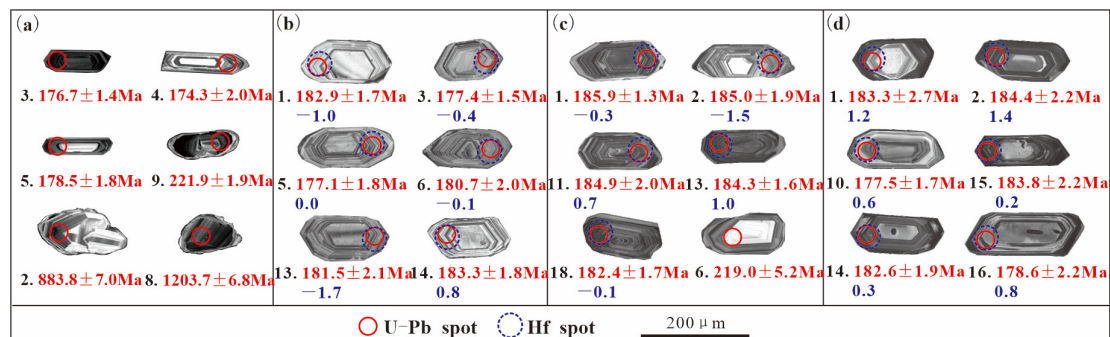


Figure 4. Cathodeluminescence (CL) images of the analyzed zircon from different intrusive rocks in the Fukeshan area. (a) Gabbro (FKS06); (b) granodiorite (FKS08); (c) porphyritic monzogranite (FKS03); (d) biotite-bearing monzogranite (FKS07). Black numbers indicate sample numbers; red numbers denote zircon U-Pb ages; dark blue numbers represent Hf isotope ages.

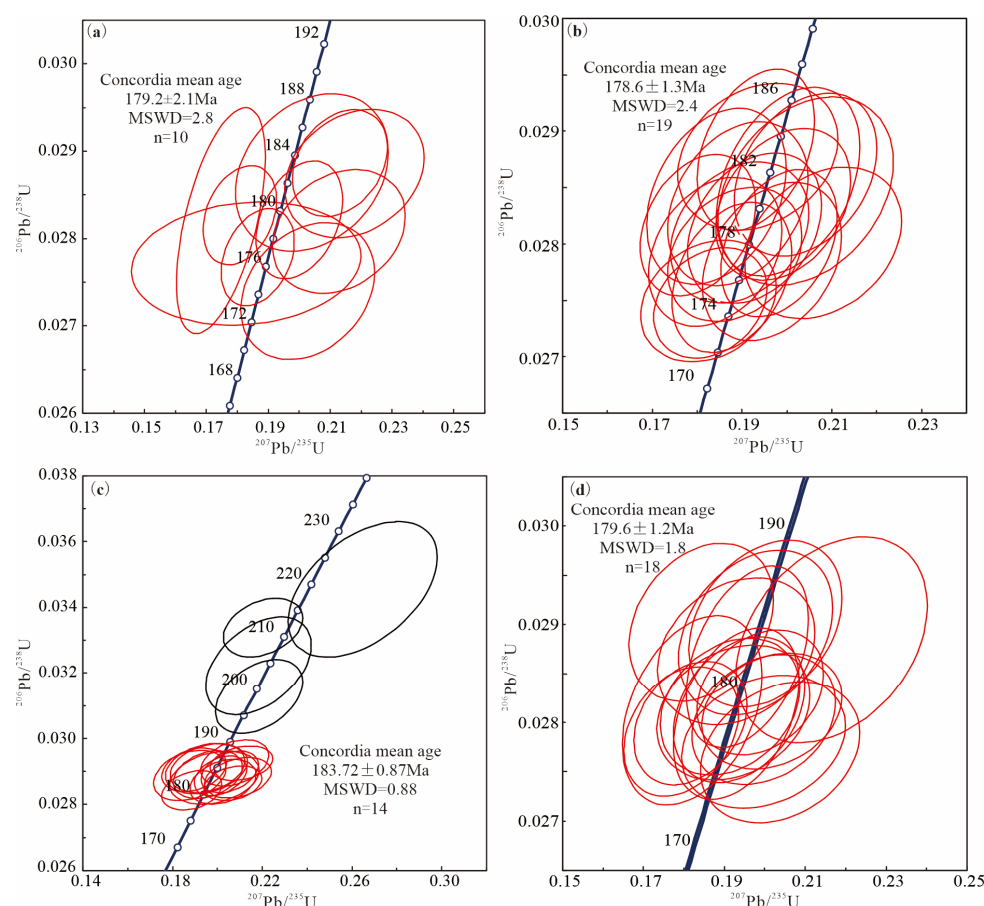


Figure 5. U–Pb concordia diagrams from intrusive rocks of the Fukeshan area. (a) Gabbro (FKS06); (b) granodiorite (FKS08); (c) porphyritic monzogranite (FKS03); (d) biotite-bearing monzogranite (FKS07).

5.1.2. Granitoid Rocks

In contrast to the gabbro, the zircon grains in this sample are abundant and readily recovered.

Granodiorite (FKS08): The zircons from this sample are predominantly short columnar shapes, with axial ratios of 2:1 to 1.2:1 and grain sizes of 100–200 μm (Figure 4b). Rhythmic banding and core–mantle structures are evident. Among the 19 analyzed test points, the Th and U contents range from 161×10^{-6} to 743×10^{-6} and 303×10^{-6} to 630×10^{-6} , respectively, with Th/U ratios of 0.5–1.4, typical of magmatic zircons. The $^{206}\text{Pb}/^{238}\text{U}$ ages range from 183.3 to 174.8 Ma, with a weighted mean age of 178.6 ± 1.3 Ma (MSWD = 2.4), corresponding to the late Early Jurassic (Figure 5b).

Porphyritic monzogranite (FKS03): In CL images, the zircons from this sample appear as short to long columnar shapes, with axial ratios of 1.2:1 to 4:1 and grain sizes of 100–200 μm (Figure 4c). Rhythmic banding and core–mantle structures are common, while some zircons display corroded cores, indicative of inherited or captured origins. Among the 18 test points, the Th and U contents range from 105×10^{-6} to 950×10^{-6} and 253×10^{-6} to 894×10^{-6} , respectively, with Th/U ratios of 0.3–0.9, consistent with magmatic origins. Fourteen zircons yield $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 186 to 180.8 Ma, with a weighted mean age of 183.72 ± 0.87 Ma (MSWD = 0.88), indicating crystallization during the late Early Jurassic. Four other zircons analyzed in their cores yield older $^{206}\text{Pb}/^{238}\text{U}$ ages of 219–198.6 Ma, corresponding to Late Triassic to Early Jurassic magmatic activity (Figure 5c).

Biotite-bearing monzogranite (FKS07): The zircons from this sample exhibit short to long columnar shapes, with axial ratios of 2:1 to 4:1 and grain sizes of 120–200 μm (Figure 4d). Rhythmic banding and core–mantle structures are prominent, and some zircons show signs of corrosion, indicating inheritance or capture. Among the 18 test points, the Th and U contents range from 80×10^{-6} to 490×10^{-6} and 257×10^{-6} to 587×10^{-6} , respectively, with Th/U ratios of 0.3–1.1, characteristic of magmatic zircons. The $^{206}\text{Pb}/^{238}\text{U}$ ages range from 184.4 to 176.2 Ma, with a weighted mean age of 179.6 ± 1.2 Ma (MSWD = 1.8), reflecting the crystallization age in the late Early Jurassic (Figure 5d).

5.2. Major Oxides

Seventeen rock samples were analyzed for their major element compositions (Table 2). The elemental variation characteristics of gabbro, gabbro-diorite, granodiorite, porphyritic monzogranite, and biotite-bearing monzogranite are detailed as follows (Figures 6 and 7).

Table 2. Major oxides (wt%), trace elements and rare-earth elements (ppm) compositions of intrusive rocks in Fukeshan area.

Lithology	Gabbroic Rocks					Granodiorite			Porphyritic Monzogranite				Biotite-Bearing Monzogranite				
Sample #	FKS 06	FKS 06-1	FKS 06-2	FKS 06-3	FKS 06-4	FKS 08	FKS 08-1	FKS 08-2	FKS 03	FKS 03-1	FKS 04	FKS 09	FKS 07	FKS 07-1	FKS 07-2	FKS 07-3	FKS 07-4
SiO ₂	56.31	49.73	49.94	49.72	49.78	67.66	67.29	67.49	70.58	71.69	71.71	71.47	75.08	74.49	74.35	74.80	74.86
TiO ₂	1.22	1.40	1.46	1.54	1.35	0.39	0.44	0.46	0.30	0.30	0.20	0.32	0.09	0.10	0.10	0.09	0.10
Al ₂ O ₃	17.78	16.29	16.19	16.10	16.12	16.79	16.49	16.84	15.71	15.23	15.17	15.51	14.12	14.08	14.06	14.21	14.10
TFeO	7.88	9.50	9.67	9.81	9.65	2.45	2.7	2.66	1.91	1.86	1.59	1.58	1.25	1.13	1.15	1.06	1.22
Fe ₂ O ₃	2.32	2.67	2.78	2.59	2.43	1.65	1.52	1.68	1.04	1.10	0.70	1.45	1.18	0.91	1.06	0.88	1.13
FeO	5.00	6.15	6.20	6.50	6.50	0.72	1.06	0.88	0.78	0.68	0.80	0.12	0.06	0.20	0.08	0.16	0.08
MnO	0.10	0.15	0.16	0.16	0.15	0.04	0.05	0.05	0.02	0.02	0.03	0.02	0.043	0.04	0.04	0.04	0.03
MgO	4.05	8.05	7.73	7.75	8.40	0.57	0.77	0.67	0.50	0.45	0.32	0.14	0.08	0.10	0.10	0.09	0.09
CaO	5.22	8.85	8.45	8.57	8.49	2.23	2.84	2.78	1.72	2.11	1.90	1.51	1.13	1.15	1.15	1.15	1.19
Na ₂ O	3.24	2.85	3.08	3.01	2.86	4.64	4.73	4.84	3.66	4.12	4.17	4.33	4.44	4.28	4.31	4.32	4.43
K ₂ O	1.61	1.04	1.10	1.06	1.16	3.35	2.95	2.88	5.24	3.47	3.32	3.27	3.28	3.48	3.48	3.42	3.30
P ₂ O ₅	0.31	0.24	0.26	0.27	0.20	0.15	0.16	0.16	0.10	0.10	0.05	0.10	0.03	0.02	0.02	0.02	0.03
LOI	1.62	1.46	1.61	1.55	1.73	0.94	1.34	0.78	0.49	0.55	1.23	1.50	0.66	0.54	0.65	0.59	0.61
Total	99.32	99.57	99.64	99.55	99.89	99.21	99.75	99.60	100.23	99.89	99.70	99.76	100.21	99.41	99.41	99.79	99.95
Na ₂ O/K ₂ O	2.02	2.75	2.80	2.83	2.46	1.39	1.60	1.68	0.70	1.19	1.26	1.32	1.35	1.23	1.24	1.26	1.34
CaO/Na ₂ O	1.61	3.11	2.74	2.85	2.97	0.48	0.60	0.57	0.47	0.51	0.46	0.35	0.25	0.27	0.27	0.27	0.27
Mg [#]	51	63	61	61	63	29	34	31	32	30	26	14	10	14	14	13	12
σ	1.67	1.99	2.24	2.18	2.12	2.59	2.43	2.43	2.87	2.01	1.95	2.03	1.86	1.91	1.94	1.88	1.88
A/NK	2.51	2.80	2.59	2.64	2.71	1.49	1.50	1.52	1.34	1.45	1.45	1.45	1.30	1.30	1.29	1.31	1.30
A/CNK	1.12	0.76	0.77	0.76	0.77	1.12	1.05	1.07	1.10	1.18	1.10	1.18	1.10	1.10	1.09	1.11	1.09
DI	50.6	31.0	33.4	32.6	31.8	82.8	80.1	80.4	87.2	86.2	86.3	88.0	91.4	91.3	91.4	91.3	91.2

Table 2. Cont.

Lithology	Gabbroic Rocks				Granodiorite				Porphyritic Monzogranite				Biotite-Bearing Monzogranite				
La	55.5	16.8	18.7	18.8	15.2	26.6	28.0	29.6	26.8	19.0	27.8	20.2	16.4	18.1	17.0	17.5	16.2
Ce	97.6	37.5	39.7	40.6	33.1	52.8	56.6	58.9	51.5	46.1	52.1	38.0	32.4	35.5	33.0	34.5	31.1
Pr	11.0	4.90	5.31	5.42	4.39	5.76	6.68	6.79	5.51	3.82	5.47	4.28	3.70	4.02	3.79	3.91	3.56
Nd	37.2	21.0	22.5	23.5	18.9	20.7	25.1	25.1	19.3	13.0	18.6	15.1	13.8	14.9	14.1	14.7	13.2
Sm	6.76	4.82	5.30	5.45	4.36	3.63	4.52	4.51	2.91	1.84	3.08	2.39	3.06	3.40	3.18	3.32	2.86
Eu	1.54	1.60	1.69	1.71	1.56	0.96	1.16	1.13	0.92	0.72	0.85	0.60	0.55	0.52	0.53	0.47	0.55
Gd	5.83	4.77	5.09	5.30	4.33	2.48	3.29	3.21	1.65	1.07	2.07	1.67	2.60	2.81	2.62	2.77	2.45
Tb	0.90	0.79	0.82	0.86	0.70	0.35	0.46	0.44	0.20	0.13	0.26	0.23	0.36	0.42	0.38	0.38	0.35
Dy	5.22	4.82	5.12	5.34	4.32	1.81	2.47	2.39	0.92	0.65	1.31	1.20	1.95	2.18	1.94	1.99	1.88
Ho	1.02	0.96	1.00	1.06	0.88	0.33	0.44	0.43	0.16	0.13	0.24	0.22	0.36	0.40	0.37	0.36	0.35
Er	2.81	2.61	2.78	2.87	2.36	0.88	1.17	1.14	0.45	0.38	0.66	0.64	0.96	1.03	0.98	0.93	0.89
Tm	0.38	0.38	0.40	0.42	0.34	0.12	0.16	0.16	0.07	0.05	0.10	0.09	0.14	0.15	0.14	0.13	0.12
Yb	2.46	2.42	2.59	2.70	2.23	0.83	1.09	1.01	0.42	0.39	0.65	0.62	0.88	0.92	0.91	0.85	0.82
Lu	0.38	0.36	0.39	0.40	0.33	0.12	0.16	0.15	0.07	0.06	0.10	0.11	0.13	0.14	0.15	0.13	0.12
Y	26.4	25.5	27.1	27.8	23.1	8.65	11.7	11.0	4.39	3.83	6.26	6.73	9.59	10.4	9.96	9.43	9.23
Li	22.5	13.9	13.5	12.3	15.3	23.3	23.9	27.1	20.3	21.6	21.0	61.4	45.5	39.3	39.9	38.4	37.8
Be	1.57	1.02	1.30	1.21	1.16	2.37	2.24	2.50	1.64	2.08	1.68	3.69	2.77	3.5	2.37	3.51	2.72
Sc	19.7	28.6	28.4	29.7	30.9	3.83	4.05	4.21	2.29	2.51	1.90	3.27	1.76	1.77	2.00	1.76	1.73
V	152	172	199	212	185	24.7	27.4	28.2	16.5	16.7	4.56	14.3	2.93	2.93	2.64	2.02	3.05
Cr	41.9	362	311	319	420	2.01	2.32	2.21	1.30	1.30	0.61	1.40	0.60	0.68	0.69	0.61	0.67
Co	22.4	38.5	36.5	35.5	38.7	3.06	3.40	3.28	2.15	2.11	1.16	1.20	0.50	0.48	0.5	0.46	0.50
Ni	16.7	97.0	88.7	89.4	109	0.85	1.11	1.05	0.56	0.63	0.33	0.44	0.35	0.32	0.34	0.26	0.37
Cu	23.4	24.2	29.2	31.9	24.4	1.51	1.62	1.65	1.26	1.23	0.83	1.05	1.11	0.85	0.86	0.83	0.96
Zn	116	95.7	93.0	91.8	108.7	57.1	61.0	60.2	51.0	50.5	42.7	39.7	41.5	46.6	40.3	46.1	56.6
Ga	22.2	17.8	17.9	18.0	17.4	22.1	22.0	22.3	19.1	20.1	18.3	22.1	17.5	17.9	17.1	17.8	17.4
Rb	53.4	34.6	35.9	34.5	39.8	87.4	82.3	80.8	103	81.2	85.6	98.2	130	130	131	128	126
Sr	459	430	455	444	420	600	580	579	410	401	396	341	221	202	219	193	222
Zr	254	159	167	182	140	199	198	208	167	172	144	165	95.9	94.5	99.0	94.9	90.7
Nb	10.1	4.56	4.71	5.04	4.67	6.80	8.46	8.45	4.97	4.60	6.28	12.9	6.91	9.78	7.94	9.87	10.9
Sn	1.24	1.11	1.13	1.08	1.15	1.14	1.38	1.40	0.66	0.68	1.52	2.90	3.32	3.88	2.87	4.50	2.82
Cs	2.10	0.92	1.14	0.98	1.11	1.68	1.30	1.92	1.08	2.35	3.99	4.34	9.89	10.00	7.93	9.06	8.68
Ba	659	327	337	319	369	1235	1084	1068	1744	816	1053	512	692	658	718	614	700
Hf	6.40	3.75	4.06	4.36	3.48	5.21	5.21	5.33	4.66	4.53	3.89	4.65	3.25	3.22	3.32	3.39	3.14
Ta	0.55	0.27	0.28	0.30	0.30	0.46	0.60	0.59	0.18	0.14	0.25	0.63	0.42	1.00	0.44	0.91	0.91
Tl	0.34	0.19	0.21	0.20	0.20	0.51	0.50	0.49	0.56	0.49	0.48	0.57	0.80	0.80	0.84	0.78	0.79
Pb	69.9	59.1	52.8	56.7	70.7	21.9	20.5	21.3	22.7	19.5	28.1	21.5	34.6	31.7	35.2	31.1	32.8
Th	13.5	2.30	2.14	2.29	2.04	4.79	4.84	5.38	5.49	4.85	7.68	10.7	6.71	7.40	7.10	7.41	6.28
U	0.83	0.42	0.42	0.45	0.39	0.67	0.81	0.88	0.56	0.54	1.03	1.32	2.29	1.76	1.87	1.93	2.00
ΣREEs	229	104	111	114	92.9	117	131	135	111	87.4	113	85.4	77.3	84.5	79.1	81.9	74.5
ΣLREEs	210	86.7	93.1	95.4	77.4	110	122	126	107	84.5	108	80.6	69.9	76.4	71.6	74.4	67.5
ΣHREEs	19.0	17.1	18.2	18.9	15.5	6.92	9.24	8.93	3.94	2.87	5.39	4.78	7.38	8.05	7.49	7.54	6.98
LREEs/HREEs	11.0	5.07	5.12	5.04	5.00	16.0	13.2	14.1	27.2	29.5	20.0	16.9	9.47	9.50	9.56	9.87	9.60
δEu	0.75	1.02	0.99	0.97	1.09	0.98	0.92	0.91	1.28	1.57	1.03	0.92	0.60	0.51	0.56	0.47	0.64
δCe	0.97	1.01	0.98	0.99	0.99	1.05	1.01	1.02	1.04	1.33	1.04	1.00	1.02	1.02	1.01	1.02	1.00
(La/Yb) _N	16.2	4.99	5.17	4.99	4.87	23.0	18.4	21.0	45.8	34.9	30.7	23.4	13.4	14.1	13.4	14.8	14.2
T _{Zr} (°C)						803	794	800	787	792	780	798	750	749	752	750	745

Note: # Sample number. Mg[#] = mole Mg/(Mg + Fe). A/CNK = mole [Al₂O₃/(CaO + Na₂O + K₂O)].

5.2.1. Mafic Rocks

The major element compositions of the mafic samples are characterized by SiO₂ (49.72–56.3 wt%), Al₂O₃ (16.1–17.78 wt%), CaO (5.22–8.85 wt%), MgO (4.05–8.4 wt%), and TiO₂ (1.22–1.54 wt%). The Rittman index (δ) ranges from 1.67 to 2.24, classifying them as calc-alkaline rocks. The Na₂O/K₂O ratios (2.02–2.83) reflect sodium enrichment. (Na₂O + K₂O) increases with the increase in SiO (Figure 6a), identifying them as high-potassium calc-alkaline series (Figure 6b).

5.2.2. Granitoid Rocks

The granodiorite samples exhibit SiO₂ (67.29–67.66 wt%), Al₂O₃ (16.49–16.84 wt%), and MgO (0.57–0.77 wt%). The total alkali content (Na₂O + K₂O) ranges from 7.68 to 7.99 wt%, and the Rittman index (δ) is 2.43–2.59, classifying them as calc-alkaline rocks. The A/CNK ratio (1.05–1.12) suggests that these rocks are in transition between peraluminous and strongly peraluminous compositions (Figure 6d). The differentiation index (DI) ranges from 80.1 to 82.8, and Mg[#] values are between 32 and 36, having an extremely high degree of differentiation. The K₂O/Na₂O ratio (0.60–0.72) indicates relative potassium enrichment. All three samples plot in the transition zone between quartz diorite and granodiorite (Figure 6a,b), further classifying them as high-potassium calc-alkaline series (Figure 6b).

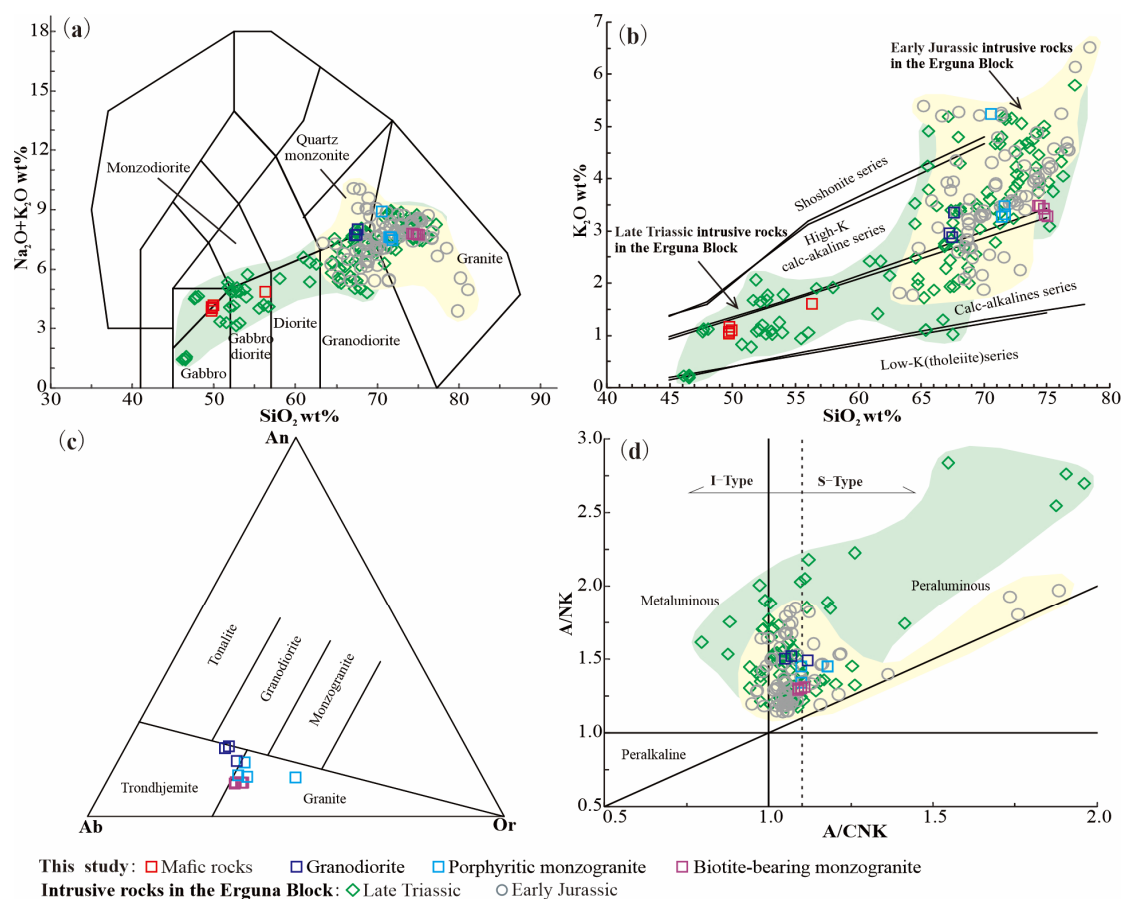


Figure 6. Major element diagrams for the volcanic rock from intrusive rocks of Fukeshan area. (a) Total alkalis against silica diagram, modified after ref. [52]; (b) Ab–An–Or diagram for granite classification, modified after ref. [53]; (c) Silica–alkali diagram for granite classification, modified after ref. [54]; (d) A/CNK–A/NK diagram of granite. The major element data of intrusive rocks in the Erguna Block (after ref. [4,6,11,43,55–61]) are listed in Supplementary Table S1.

The porphyritic monzogranite samples have components of SiO_2 (70.88–71.71 wt%), Al_2O_3 (15.17–15.71 wt%), and MgO (0.14–0.50 wt%). The total alkali content ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) ranges from 7.49 to 8.9 wt%, with a Rittman index (δ) of 1.95–2.87, classifying them as calc-alkaline rocks. The differentiation index (DI) ranges from 86.2 to 88.0, and $\text{Mg}^\#$ values range from 15 to 34, having an extremely high degree of differentiation. The $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio (0.76–1.43) indicates relative potassium enrichment. The A/CNK ratio (1.10–1.18) suggests that the rocks are strongly peraluminous (Figure 6d). In the ($\text{Na}_2\text{O} + \text{K}_2\text{O}$)– SiO_2 diagram, all samples plot in the granite field (Figure 6a,b).

The biotite-bearing monzogranite samples are characterized by SiO_2 (74.35–75.08 wt%), Al_2O_3 (14.06–14.21 wt%), and MgO (0.08–0.10 wt%). The total alkali content ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) ranges from 7.72 to 7.79 wt%, with a Rittman index (δ) of 1.88–1.94, classifying them as calc-alkaline rocks. The DI ranges from 91.2 to 91.4, and $\text{Mg}^\#$ values range from 11 to 15, reflecting a high degree of differentiation. The $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios (0.74–0.81) indicate relative potassium enrichment. In the ($\text{Na}_2\text{O} + \text{K}_2\text{O}$)– SiO_2 diagram, all samples plot in the granite field (Figure 6a), classified as high-potassium calc-alkaline to calc-alkaline transitional rocks (Figure 6b). The A/CNK ratio (1.09–1.11) suggests a transition between peraluminous and strongly peraluminous compositions (Figure 6d).

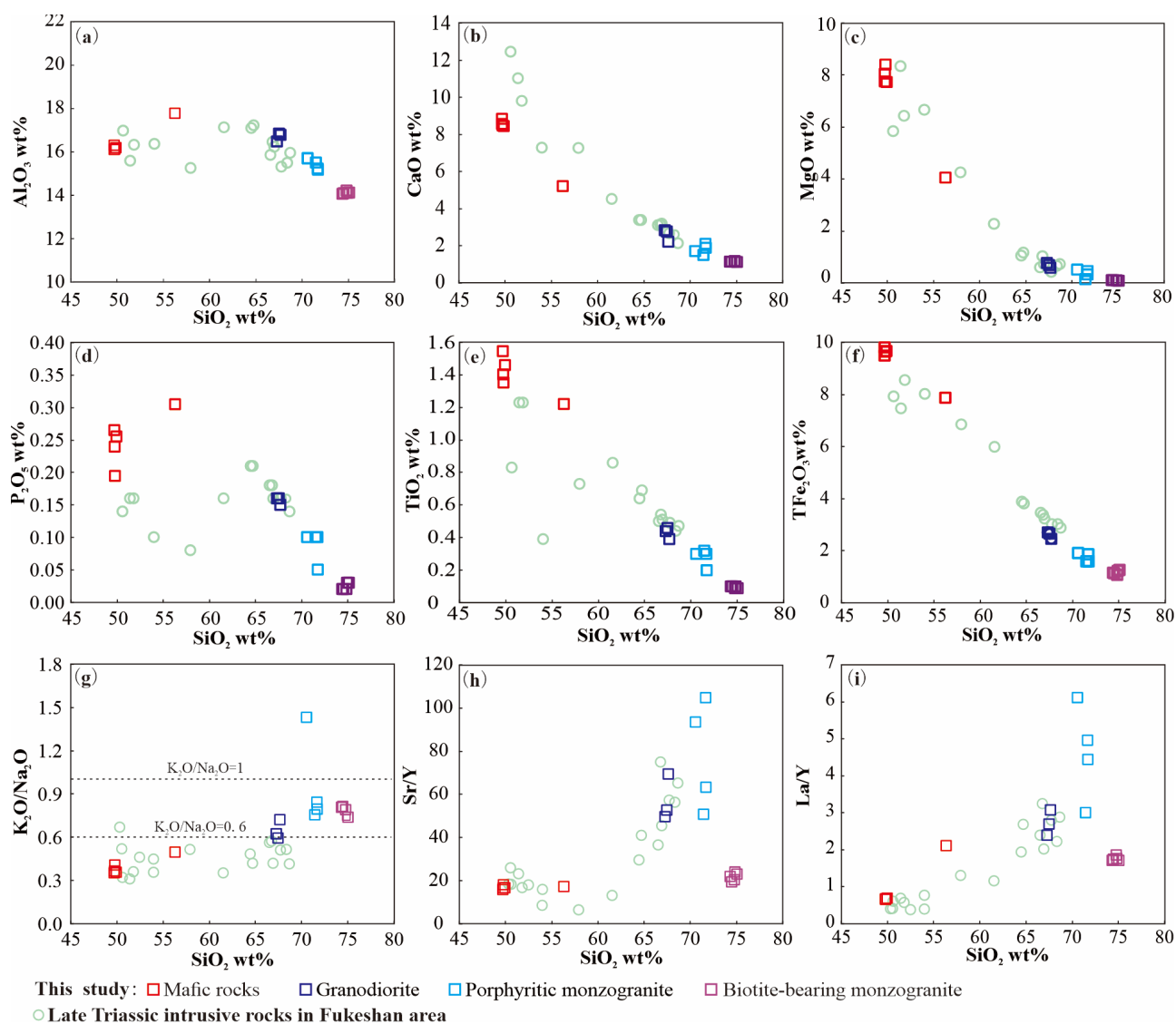


Figure 7. Harker diagram of some major oxides and trace elements vs. SiO_2 from intrusive rocks of Fukeshan area. (a) Al_2O_3 vs. SiO_2 ; (b) CaO vs. SiO_2 ; (c) MgO vs. SiO_2 ; (d) P_2O_5 vs. SiO_2 ; (e) TiO vs. SiO_2 ; (f) TFe_2O_3 vs. SiO_2 ; (g) $(\text{K}_2\text{O}/\text{Na}_2\text{O})$ vs. SiO_2 ; (h) (Sr/Y) vs. SiO_2 ; (i) (La/Y) vs. SiO_2 .

5.3. Trace Elements

The trace element compositions of the studied rock samples revealed significant geochemical variations between different lithologies.

5.3.1. Mafic Rocks

The total rare-earth element (REE) content of the mafic samples ranges from 92.9×10^{-6} to 229×10^{-6} , with an average of 130×10^{-6} . The light-to-heavy rare-earth element ratio (LREEs/HREEs) varies between 5.04 and 11.0, while the $(\text{La}/\text{Yb})_N$ ratio ranges from 4.87 to 16.2, indicating relative enrichment in LREEs. The δEu values range from 0.75 to 1.09, reflecting a slight negative or no Eu anomaly. In the chondrite-normalized REE diagram (Figure 8a) and primitive mantle-normalized spider diagram (Figure 8b), the samples display enrichment in LREEs, Pb, and LILEs, along with depletion in HFSEs and HREEs.

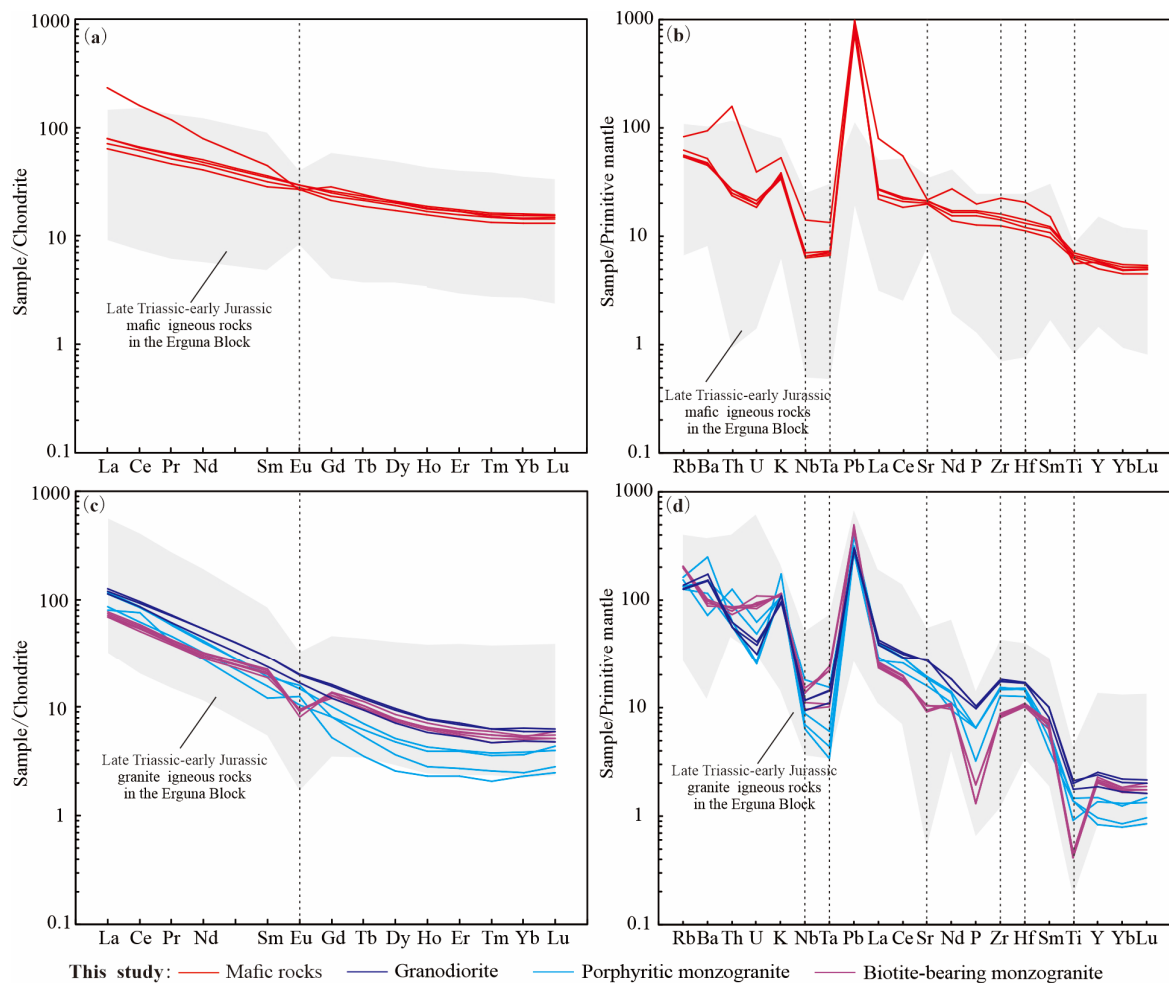


Figure 8. Chondrite-normalized rare-earth element patterns and primitive mantle-normalized trace element spider diagrams from intrusive rocks of Fukeshan area (modified after refs. [62,63]), (a) Mafic rocks from the Fukeshan area and Late Triassic–Early Jurassic mafic igneous rocks from the Erguna Block; (b) mafic rocks from the Fukeshan area and Late Triassic–Early Jurassic mafic igneous rocks from the Erguna Block; (c) granitoid rocks from the Fukeshan area and Late Triassic–Early Jurassic granitic rocks from the Erguna Block; (d) granitoid rocks from the Fukeshan area and Late Triassic–Early Jurassic granitic rocks from the Erguna Block. The rare element and trace element data of intrusive rocks in the Erguna Block (after ref. [4,6,11,43,55–61]) are listed in Supplementary Table S1.

5.3.2. Granitoid Rocks

The granodiorite samples have total REE contents ranging from 117×10^{-6} to 135×10^{-6} , with an average of 128×10^{-6} . The LREEs/HREEs ratios range between 13.2 and 16.0, while the $(La/Yb)_N$ ratios are between 18.4 and 23.0, indicating pronounced differentiation between LREEs and HREEs. The δEu values range from 0.91 to 0.98, showing a weak negative Eu anomaly. These patterns suggest enrichment in LREEs and LILEs, similar to typical arc magmas (Figure 8c,d).

The total REE content of the porphyritic monzogranite samples varies from 85.4×10^{-6} to 113×10^{-6} , with an average of 99×10^{-6} . The LREEs/HREEs ratios range between 16.9 and 29.5, while the $(La/Yb)_N$ ratios span from 18.4 to 45.8, indicating significant differentiation between LREEs and HREEs. The δEu values range from 0.92 to 1.57, suggesting no significant Eu anomaly. In trace element diagrams, these samples show enrichment in LREEs, Pb, Zr, Hf, and LILEs. They are depleted in HFSEs and HREEs (Figure 8c,d).

The biotite-bearing monzogranite samples have total REE contents ranging from 74.5×10^{-6} to 84.5×10^{-6} , with an average of 79.5×10^{-6} , which is slightly lower than that

of the porphyritic monzogranite. The LREEs/HREEs ratios range from 9.47 to 9.87, while $(\text{La/Yb})_N$ ratios vary between 13.4 and 14.8, indicating moderate differentiation between LREEs and HREEs. The δEu values range from 0.46 to 0.62, reflecting a pronounced negative Eu anomaly. Similar to other samples, the biotite-bearing monzogranite exhibits enrichment in LREEs, Pb, Zr, Hf, and LILEs, with depletion in HFSEs and HREEs, which is consistent with the geochemical characteristics of arc magmas (Figure 8c,d).

The geochemical characteristics of granitoid rocks are marked by elevated abundances of LREEs and LILEs, coupled with depleted abundances of HFSEs and HREEs. This elemental pattern is characteristic of arc-related volcanic magma sources.

5.4. Whole-Rock Sr–Nd Isotope

The results of the whole-rock Sr–Nd isotopic analyses for the late Early Jurassic intrusive rocks from the Fukeshan area are presented in Table 3 and Figure 9.

Table 3. Sr–Nd isotopic compositions from intrusive rocks of Fukeshan area.

Sample #	T (Ma)	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	2σ	$(^{87}\text{Sr}/^{86}\text{Sr})_i$	$(^{143}\text{Nd}/^{144}\text{Nd})_i$	$\varepsilon_{\text{Nd}}(t)$	T_{DM1} (Ma)	T_{DM2} (Ma)
FKS06	179.2	0.708578	0.512380	0.000016	0.707721	0.512251	−3.0	1132	1213
FKS06-1	179.2	0.707297	0.512674	0.000006	0.706704	0.512511	2.0	971	800
FKS06-2	179.2	0.707801	0.512679	0.000006	0.707219	0.512512	2.0	1009	798
FKS06-3	179.2	0.707596	0.512674	0.000005	0.707023	0.512510	2.0	990	802
FKS03	183.7	0.709466	0.512337	0.000009	0.707562	0.512228	−3.4	1012	1245
FKS04	183.7	0.709236	0.512362	0.000008	0.707735	0.512229	−3.4	1166	1243
FKS09	183.7	0.708510	0.512381	0.000012	0.707449	0.512254	−2.9	1086	1203
FKS08	178.6	0.708548	0.512369	0.000008	0.707479	0.512245	−3.2	1105	1223
FKS07	179.5	0.711506	0.512449	0.000008	0.707163	0.512291	−2.3	1347	1149

Note: # Sample number.

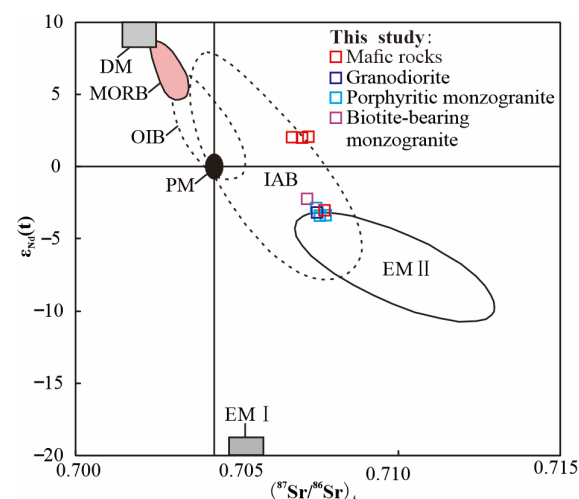


Figure 9. Sr–Nd isotopic diagram of the intrusive rocks of the Fukeshan area (modified after [64]). EMI and EMII represent two types of mantle end-members [65].

5.4.1. Mafic Rocks

The mafic rocks exhibit $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ranging from 0.707297 to 0.708578 and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios between 0.512380 and 0.512679. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ values $((^{87}\text{Sr}/^{86}\text{Sr})_i)$ range from 0.706704 to 0.70772, with $\varepsilon_{\text{Nd}}(t)$ values varying between −3.4 and 2.0. The Nd two-stage model ages (T_{DM2}) are between 798 and 1213 Ma, suggesting that the source material for these rocks was formed during the Neoproterozoic to Mesoproterozoic eras.

5.4.2. Granitoid Rocks

The granitoid rocks exhibit $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ranging from 0.70851 to 0.711506 and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios ranging from 0.512337 to 0.512449. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ values ($(^{87}\text{Sr}/^{86}\text{Sr})_i$) range from 0.707163 to 0.707735, with $\epsilon_{\text{Nd}}(t)$ values between -3.4 and -2.3 . The Nd two-stage model ages (T_{DM2}) range from 1149 to 1245 Ma, indicating a Mesoproterozoic origin for the source materials.

5.5. Zircon Hf Isotope

The zircon Lu–Hf isotopic results for the late Early Jurassic intrusive rocks from the Fukeshan area are summarized in Table 4 and illustrated in Figure 10.

Table 4. Zircon Lu–Hf isotopic data.

Sample #	T (Ma)	$^{176}\text{Yb}/^{177}\text{Hf}$	1σ	$^{176}\text{Lu}/^{177}\text{Hf}$	1σ	$^{176}\text{Hf}/^{177}\text{Hf}$	1σ	$\epsilon_{\text{Hf}}(0)$	$\epsilon_{\text{Hf}}(t)$	T_{DM1} (Ga)	T_{DM} (Ma)	$f_{\text{Lu/Hf}}$
FKS08 Granodiorite												
1	182.9	0.038460	0.000491	0.001139	0.000018	0.282634	0.000016	−4.87	−1.0	879	1289	−0.97
3	177.4	0.029762	0.000096	0.000890	0.000008	0.282653	0.000013	−4.22	−0.4	847	1250	−0.97
5	177.1	0.033725	0.000303	0.001053	0.000014	0.282666	0.000012	−3.76	0.0	833	1222	−0.97
6	180.7	0.025191	0.000671	0.000811	0.000009	0.282661	0.000011	−3.93	−0.1	834	1229	−0.98
7	174.8	0.035153	0.000692	0.001063	0.000010	0.282678	0.000015	−3.33	0.4	815	1195	−0.97
12	176.2	0.030927	0.000421	0.000905	0.000010	0.282654	0.000012	−4.17	−0.4	846	1247	−0.97
13	181.5	0.031950	0.000615	0.000942	0.000013	0.282615	0.000014	−5.54	−1.7	901	1331	−0.97
14	183.3	0.034648	0.000578	0.000990	0.000019	0.282684	0.000013	−3.12	0.8	805	1176	−0.97
17	178.1	0.038334	0.000730	0.001018	0.000014	0.282663	0.000013	−3.87	−0.1	836	1228	−0.97
19	181.0	0.028277	0.000627	0.000938	0.000006	0.282661	0.000012	−3.94	−0.1	837	1230	−0.97
FKS03 Porphyritic monzogranite												
1	185.9	0.044625	0.001330	0.001159	0.000022	0.282651	0.000011	−4.27	−0.3	855	1250	−0.97
2	185.0	0.027156	0.000790	0.000721	0.000018	0.282617	0.000012	−5.50	−1.5	894	1325	−0.98
7	184.6	0.020658	0.000396	0.000556	0.000007	0.282651	0.000011	−4.27	−0.3	842	1246	−0.98
9	183.7	0.023600	0.000339	0.000697	0.000009	0.282669	0.000012	−3.64	0.3	820	1207	−0.98
10	180.8	0.037587	0.000650	0.000965	0.000011	0.282670	0.000014	−3.61	0.2	824	1209	−0.97
11	184.9	0.033403	0.000404	0.000890	0.000007	0.282679	0.000013	−3.27	0.7	809	1184	−0.97
12	182.1	0.038584	0.000603	0.000998	0.000011	0.282678	0.000012	−3.32	0.6	814	1190	−0.97
13	184.3	0.034304	0.000378	0.000932	0.000009	0.282688	0.000012	−2.97	1.0	798	1166	−0.97
16	183.6	0.027937	0.000785	0.000825	0.000028	0.282682	0.000013	−3.20	0.7	805	1180	−0.98
18	182.4	0.024801	0.000279	0.000723	0.000007	0.282659	0.000013	−4.01	−0.1	835	1232	−0.98
FKS07 Biotite-bearing monzogranite												
1	183.3	0.054355	0.000873	0.001316	0.000012	0.282698	0.000014	−2.63	1.2	793	1148	−0.96
2	184.4	0.055664	0.001503	0.001384	0.000041	0.282701	0.000013	−2.51	1.4	789	1140	−0.96
3	178.0	0.026719	0.000627	0.000807	0.000014	0.282661	0.000013	−3.94	−0.1	834	1230	−0.98
5	182.2	0.054193	0.000500	0.001424	0.000017	0.282749	0.000012	−0.82	3.0	722	1034	−0.96
7	184.4	0.027685	0.000542	0.000793	0.000006	0.282618	0.000016	−5.45	−1.5	894	1323	−0.98
10	177.5	0.026036	0.000423	0.000798	0.000012	0.282682	0.000012	−3.17	0.6	803	1182	−0.98
12	178.8	0.027119	0.000482	0.000792	0.000018	0.282678	0.000011	−3.34	0.5	810	1192	−0.98
14	182.6	0.049566	0.000730	0.001438	0.000033	0.282671	0.000012	−3.58	0.3	834	1210	−0.96
15	183.8	0.096529	0.000862	0.002318	0.000012	0.282670	0.000017	−3.60	0.2	855	1217	−0.93
16	178.6	0.033006	0.000847	0.000963	0.000012	0.282688	0.000015	−2.99	0.8	800	1171	−0.97

Note: Calculation in this study: $\epsilon_{\text{Hf}}(0) = [(^{176}\text{Hf}/^{177}\text{Hf})_{\text{S}} / (^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR},0} - 1] \times 10,000$; $\epsilon_{\text{Hf}}(t) = \{[(^{176}\text{Hf}/^{177}\text{Hf})_{\text{S}} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{S}} \times (e^{\lambda t} - 1)] / [(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR},0} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR},0} \times (e^{\lambda t} - 1)] - 1\} \times 10,000$; $T_{\text{DM1}} = 1/\lambda \times \ln[1 + ((^{176}\text{Hf}/^{177}\text{Hf})_{\text{S}} - (^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}}) / ((^{176}\text{Lu}/^{177}\text{Hf})_{\text{S}} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}})]$; $T_{\text{DM2}} = T_{\text{DM1}} - (T_{\text{DM1}} - t) \times (f_{\text{CC}} - f_{\text{S}}) \times (f_{\text{CC}} - f_{\text{DM}})$; and $f_{\text{Lu/Hf}} = [(^{176}\text{Lu}/^{177}\text{Hf})_{\text{S}} / (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR},0}] - 1$; where $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{S}}$ and $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{S}}$ are measured values of samples, s = sample, t = crystallization time of zircon; $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR},0} = 0.0332$ and $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR},0} = 0.282772$ [66]; $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}} = 0.0384$ and $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}} = 0.28325$ [67]; $f_{\text{CC}} = -0.55$ and $f_{\text{DM}} = 0.16$; $\lambda = 1.867 \times 10^{-12} \text{yr}^{-1}$ [68] was used in the calculation. # Sample number.

Granodiorite: The zircons from the granodiorite samples exhibit $\epsilon_{\text{Hf}}(t)$ values ranging from -1.7 to 0.8 , with an average of -0.3 . The zircon two-stage model ages (T_{DM2}) range from 1331 to 1176 Ma, corresponding to Mesoproterozoic crustal sources. **Porphyritic Monzogranite:** In the porphyritic monzogranite, the zircon $\epsilon_{\text{Hf}}(t)$ values range from -1.5 to 1 , with an average of 0.1 . The zircon two-stage model ages (T_{DM2}) range from 1325 to 1166 Ma, indicating contributions from Mesoproterozoic crustal materials. **Biotite-bearing monzogranite:** The zircons from the biotite-bearing monzogranite show $\epsilon_{\text{Hf}}(t)$ values ranging from -1.5 to 3 , with an average of 0.6 . The zircon two-stage model ages (T_{DM2}) range from 1323 to 1034 Ma, suggesting a dominant Mesoproterozoic crustal contribution with potential minor mantle input.

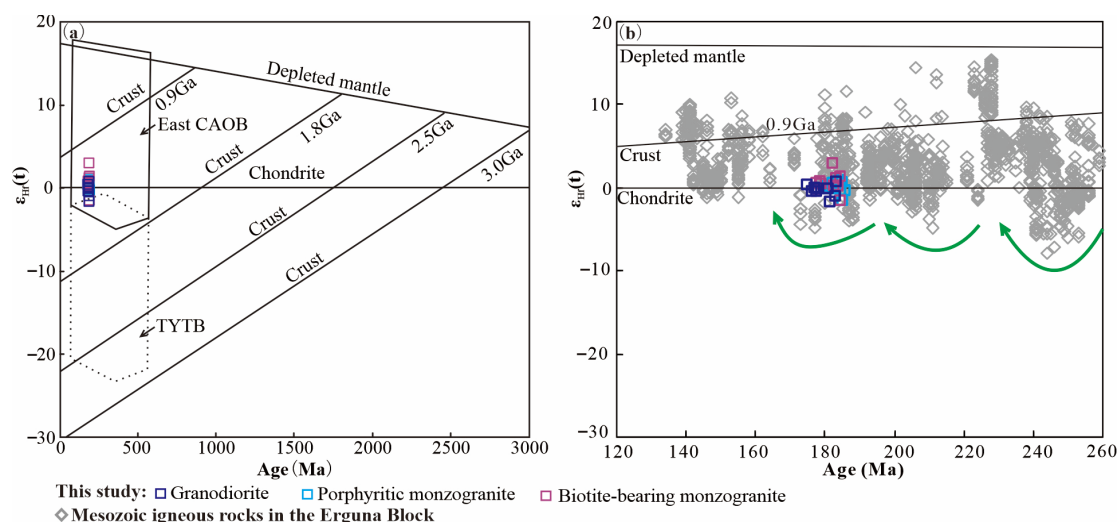


Figure 10. $\epsilon_{\text{Hf}}(t)$ vs. U–Pb age diagram from intrusive rocks of Fukeshan area (modified after [69]). (a) Correlations between zircon $\epsilon_{\text{Hf}}(t)$ value and age; (b) Detailed plot of zircon $\epsilon_{\text{Hf}}(t)$ value against age. Abbreviations: CAOB, Central Asian Orogenic Belt; YFTB, Yanshan Fold and Thrust Belt. The Hf data of intrusive rocks in the Erguna Block (after ref. [4,6,11,56–61,70–80]) are listed in Supplementary Table S2.

6. Discussion

6.1. Intrusion Ages

The continental arc-type magmatic rocks within the study area were dominated by granitic rocks, primarily occurring as batholiths, with fewer intermediate-basic intrusions, representing significant products of early Mesozoic magmatic activity in the Erguna block. This was consistent with the situation that Mesozoic intrusions were extensively developed in the Erguna block [11,80,81]. These rocks were significantly enriched in LREEs and LILEs but depleted in HFSEs, characteristic of calc-alkaline magmatism in subduction zones in the northern Greater Xing'an Range [11,21,27,80–86]. The zircon U–Pb ages from the granitic rocks constrained the timing of felsic magmatism, while those from the mafic rocks recorded the age of coeval mantle-derived mafic magmatism [11,43,61,81,84].

The analyzed zircons exhibited distinct characteristics of magmatic zircons, including rhythmic zoning and high Th/U ratios, confirming that the obtained ages represented the timing of crystallization. Zircon U–Pb dating yielded crystallization ages of 179 ± 2.1 Ma for the gabbro, 178.6 ± 1.3 Ma for the granodiorite, 183.72 ± 0.87 Ma for the porphyritic monzogranite, and 179.6 ± 1.2 Ma for the biotite-bearing monzogranite. These ages placed the studied rocks in the late Early Jurassic. The late Early Jurassic continental arc-type magmatic rocks within the study area represent significant products of early Mesozoic magmatic activity in the Erguna block.

6.2. Genesis and Magma Source

6.2.1. Mafic Rocks

The mafic rocks from the Fukeshan area exhibited whole-rock $\epsilon_{\text{Nd}}(t)$ values of -3.0 to 2.0 , suggesting a heterogeneous mantle source metasomatized by subduction-related components [87]. Their MgO (4.05–8.40 wt%), $\text{Mg}^\#$ (51–63), Cr (41.9–420 ppm), and Ni (16.7–109 ppm) contents were lower than those of primary mantle melts [88], indicating fractional crystallization during ascent. Trace element characteristics showed enrichment in LREEs, Pb, and LILEs, with depletion in HFSEs and HREEs (Figure 8a,b), consistent with island arc basalt (IAB) signatures [34,89]. These features indicated formation through partial melting of the lithospheric mantle metasomatized by fluids and melts from the subduct-

ing slab [11,43,81,84,90]. Relatively stable $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and $\varepsilon_{\text{Nd}}(t)$ values, combined with moderate SiO_2 and MgO contents (Figure 11a,b), indicated minimal crustal contamination.

The positive correlations between Rb/Y , Ba , and Nb/Y (Figure 11c,d) further supported slab-fluid metasomatism of an enriched mantle source [91]. Th/Yb versus Ba/La and Th/Sm versus Th/Ce relationships (Figure 11e,f) also suggested sediment involvement in mantle metasomatism [92]. Inherited zircons with Neoproterozoic and Mesoproterozoic ages, consistent with the Erguna block basement, corroborated terrigenous sediment input from the subducting MOO slab [81]. In summary, these mafic rocks formed through partial melting of a metasomatized mantle wedge, with subsequent fractional crystallization during magma ascent (Figure 11g,h).

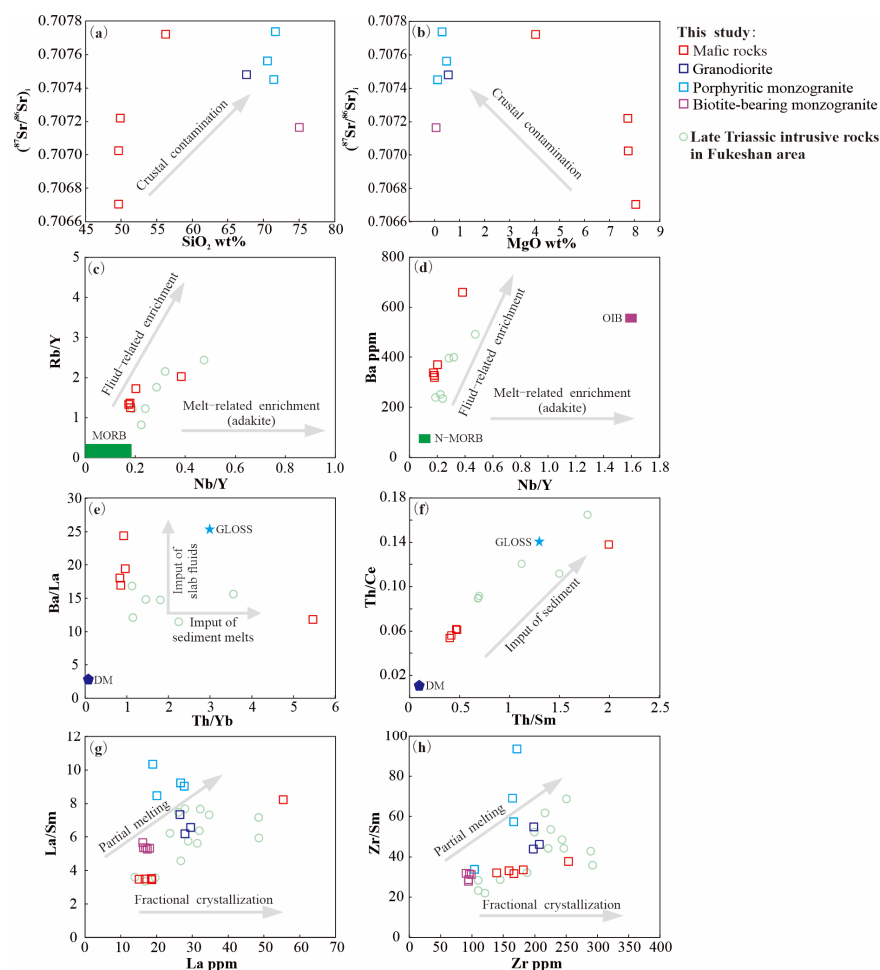


Figure 11. Diagrams of genetic types of intrusive rocks from Fukeshan area. (a) $(^{87}\text{Sr}/^{86}\text{Sr})_i$ vs. SiO_2 ; (b) $(^{87}\text{Sr}/^{86}\text{Sr})_i$ vs. MgO ; (c) Rb/Y vs. (Nb/Y) and (d) Ba vs. (Nb/Y) , modified after ref. [91]; (e) Ba/La vs. (Th/Yb) , modified after ref. [93]; (f) Th/Ce vs. (Th/Sm) , modified after ref. [92]; (g) La/Sm vs. La , modified after ref. [94]; (h) Zr vs. Zr/Sm . Global subducting sediment (GLOSS) compositions are from ref. [95].

6.2.2. Granite

The late Early Jurassic granites exhibited $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.70851–0.711506, $\varepsilon_{\text{Nd}}(t)$ values of -3.4 to -2.3 , and $T_{\text{DM}2}$ ages of 1245–1149 Ma, indicating significant ancient crustal contributions. The zircon $\varepsilon_{\text{Hf}}(t)$ values (-1.7 to 0.8) and $T_{\text{DM}2}$ ages (1331–1034 Ma) supported involvement of Mesoproterozoic crustal material with minor mantle input [96] (Figures 9 and 10). The geochemical patterns (Figure 8c,d) suggested that the granodiorites and porphyritic monzogranites shared a common magma source, mainly Mesoproterozoic

crust and evolutionary history. By contrast, the biotite-bearing monzogranite displayed distinct negative Eu anomalies, U enrichment, and lower zircon saturation temperatures (749–752 °C vs. 780–803 °C), suggesting a shallower source. Their slightly higher $\varepsilon_{\text{Hf}}(t)$ values indicated greater mantle contribution. These findings revealed complex crust–mantle interactions along the northern Erguna block margin during the late Early Jurassic.

6.2.3. Granodiorite and Porphyritic Monzogranite

The granodiorites and porphyritic monzogranites displayed adakitic characteristics [97,98] (Figure 12a,b): high SiO_2 (67.29–71.71 wt%, >56 wt%), Sr (341–600 ppm, with one sample slightly below 400 ppm), Sr/Y (49.6–105, >20), and $(\text{La}/\text{Yb})_{\text{N}}$ (18.4–45.8, >10), with low HREEs and Y (3.80–11.7 ppm, <18 ppm), and weak or absent negative Eu anomalies. Their low MgO (0.14–0.77 wt%) and $\text{Mg}^\#$ (14–34) (Figure 12c,d), together with low Cr and Ni contents, pointed to partial melting of the thickened lower crust rather than subducted oceanic slab [99]. This interpretation was supported by their $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios (0.7–1.68), which were lower than typical slab-melt adakites (2.5–6.5) [100], and their relatively high K_2O contents (2.88–5.24 wt%). The absence of negative correlations between Al_2O_3 and SiO_2 or positive Sr/Y– SiO_2 trends (Figure 7a,h,i) argued against fractional crystallization of basaltic magma [101,102]. Decreasing MgO with increasing $(^{87}\text{Sr}/^{86}\text{Sr})_{\text{i}}$ and SiO_2 (Figure 11a,b) suggested minor crustal contamination during ascent. Collectively, results indicated that these adakitic rocks formed primarily through partial melting of the thickened lower crust, with limited crustal contamination during magma ascent.

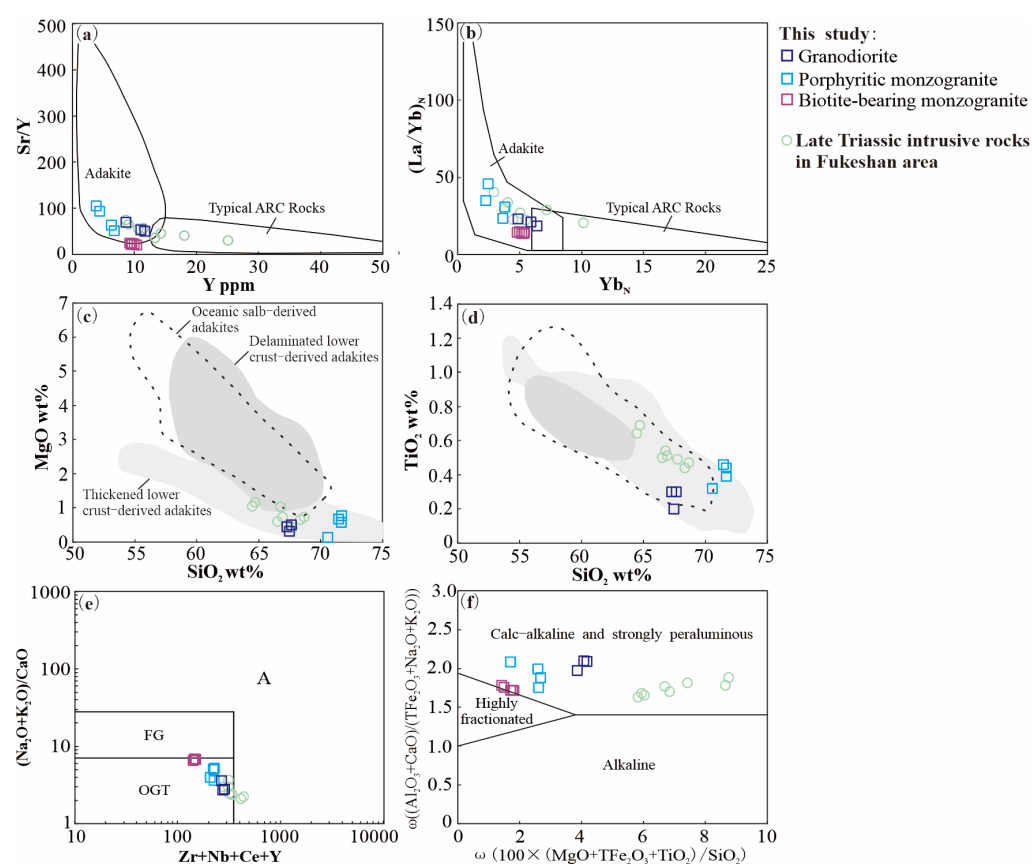


Figure 12. Cont.

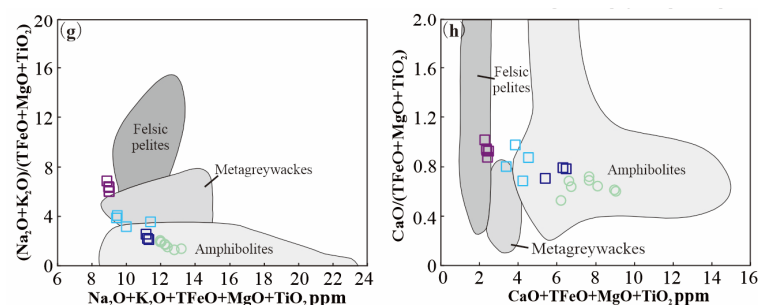


Figure 12. Diagrams of genetic types of intrusive rocks from Fukeshan area. (a) Sr/Y vs. Y and (b) $(La/Yb)_N$ vs. Yb_N diagram (modified from [97]), where N means normalized to chondrite [62]; (c) MgO vs. SiO_2 and (d) TiO_2 vs. SiO_2 diagram (modified from ref. [103]); (e) $(Zr + Nb + Ce + Y) - (K_2O + Na_2O)/CaO$ diagram (modified after ref. [104]); (f) $(Al_2O_3 + CaO)/(FeO^T + Na_2O + K_2O)$ vs. $100(MgO + FeO^T + TiO_2)/SiO_2$ diagram (modified after ref. [105]); (g) $(Na_2O + K_2O + TFeO + MgO + TiO_2)$ vs. $(Na_2O + K_2O)/(TFeO + MgO + TiO_2)$ and (h) $(CaO + TFeO + MgO + TiO_2)$ vs. $(CaO)/(TFeO + MgO + TiO_2)$ diagrams (modified after ref. [106]).

6.2.4. Biotite-Bearing Monzogranite

The biotite-bearing monzogranite was characterized by high SiO_2 ; elevated alkalis and Rb; low MgO, CaO, Cr, Ni, and Co; and depletions in Ba, Nb, Ta, Sr, P, and Ti; with a pronounced negative Eu anomaly. These features aligned partially with A-type granites [107] and high-silica granites [108,109]. However, $10,000 \times Ga/Al$ values (2.3–2.4) and the Zr contents (90.7–99.0 ppm) were lower than those of typical A-type granites, and the T_{Zr} values (745–752 °C) were comparable to those of I-type granites, indicating a highly differentiated I-type affinity. The rock plotted in the transition zone between common and highly differentiated granites (Figure 12e,f), with low Zr/Hf (~29.1 vs. continental crust 35.7 [110]) and Nb/U (~4.7 vs. upper crust 4.4 [110]) ratios. This interpretation was supported by its geochemical signatures, which reflected a felsic pelitic source (Figure 12g,h). These features, combined with depletion in Sr, Eu, and Ba, indicated significant fractional crystallization of plagioclase and biotite from a dominantly crustal source with a relatively high degree of magma differentiation.

6.3. Tectonic Setting and Geodynamic Significance

In the Fukeshan area, magmatism during the Late Triassic and late Early Jurassic is represented by typical continental arc magmatic rocks distributed parallel to the MOO subduction zone (Figure 13). These rocks showed enrichment in LREEs and LILEs and depletion in HFSEs, typical of calc-alkaline magmatism in a subduction zone setting [11,27,43,83,84]. The Late Triassic intrusions, characterized by tholeiitic to calc-alkaline and adakitic compositions, exhibited enrichment in LREEs and LILEs and depletion in HFSEs. These features, combined with their spatial distribution, suggested southward subduction of the MOO slab [43]. By contrast, the late Early Jurassic rocks showed a progression from calc-alkaline to high-potassium calc-alkaline compositions, with increasing peraluminosity, differentiation intensity, and crustal maturity. This magmatic evolution likely reflects a transition from ocean–continent subduction to continent–continent collision (Figure 13c,d).

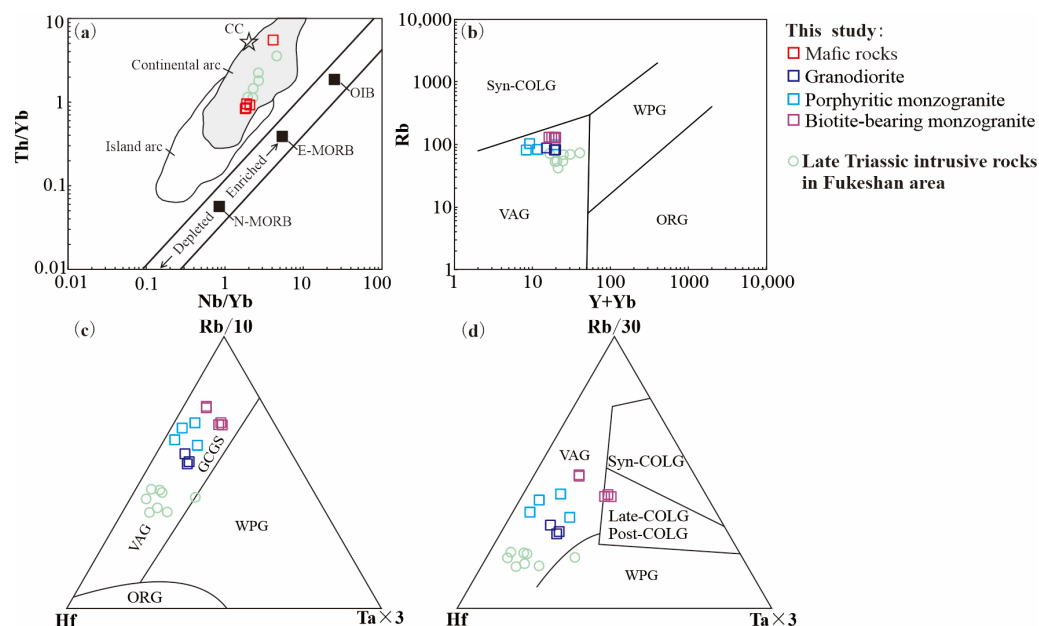


Figure 13. (a) Nb/Yb vs. Th/Yb diagrams, modified after ref. [111]; (b) Rb vs. (Y + Nb) diagrams, modified after ref. [112]; (c,d) Hf–Rb–Ta triangle diagram, modified after ref. [113]. VAG = volcanic arc granites; WPG = within-plate granites; Syn-COLG = syn-collision granites; Post-COLG = post-collision granites.

Slab rollback has been widely recognized as a key geodynamic process in subduction zones, driving upper plate extension, arc migration, and enhanced crust–mantle interactions [114–116]. Theoretical and analog modeling studies have demonstrated that slab rollback occurs when the subducting slab’s sinking velocity exceeds the convergence rate, leading to trench retreat and toroidal flow in the mantle wedge [115,117]. This process induces upwelling of asthenospheric material, promotes melting of the metasomatized mantle wedge, and generates distinct temporal–spatial variations in arc magmatism [116].

From a temporal perspective, subduction processes at convergent margins can be divided into early and late stages [118]. During the early stage, low-angle subduction leads to crustal thickening through stacking, often without significant arc magmatism [119]. In the late stage, high-angle subduction and slab rollback enhance crust–mantle interactions, inducing partial melting of the mantle wedge and crust to produce mafic and felsic arc magmas [120]. In the Fukeshan area, there were decreased $\varepsilon_{\text{Hf}}(t)$ values, which indicated extensive crust–mantle interactions. In addition, the $\varepsilon_{\text{Hf}}(t)$ values of Mesozoic intrusive rocks in the Erguna block showed distinct positive and negative peaks during the Late Triassic and late Early Jurassic (Figure 10b). Continuous subduction caused crustal thickening and facilitated mixing between crustal materials and mantle-derived magmas, leading to reduced $\varepsilon_{\text{Hf}}(t)$ values, reflecting intense crust–mantle interactions linked to slab rollback in the late stage [27].

The Late Triassic magmatic rocks in the Fukeshan area exhibited typical features of continental arc magmatism, likely related to high-angle subduction during slab rollback in the late subduction stage. By contrast, the late Early Jurassic magmatic rocks displayed high-K calc-alkaline and peraluminous characteristics, consistent with further slab rollback. This two-stage magmatic evolution, with progressively more evolved compositions, matches the predicted consequences of sustained rollback, where continued trench retreat allows for greater crustal assimilation and differentiation [114,117]. These observations indicated that MOO subduction continued until approximately 179 Ma, transitioning to collision and closure between the Early and Middle Jurassic [20,30].

In summary, the MOO experienced two major slab rollback events during the Late Triassic and late Early Jurassic, driving complex crust–mantle evolution along the northern margin of the Erguna block (Figure 14). Fluids and sediments from the subducted slab metasomatized the mantle wedge, triggering partial melting and the generation of mantle-derived magmas. These magmas underplated the thickened crust, inducing partial melting of crustal materials and producing two phases of continental magmatic arcs. The arcs migrated spatially from northwest to southeast, evolving in geochemical composition and reflecting the transition from subduction to collision. This process provides valuable insights into crustal growth, deep crust–mantle interactions, and the evolution of continental margins during MOO subduction and closure.

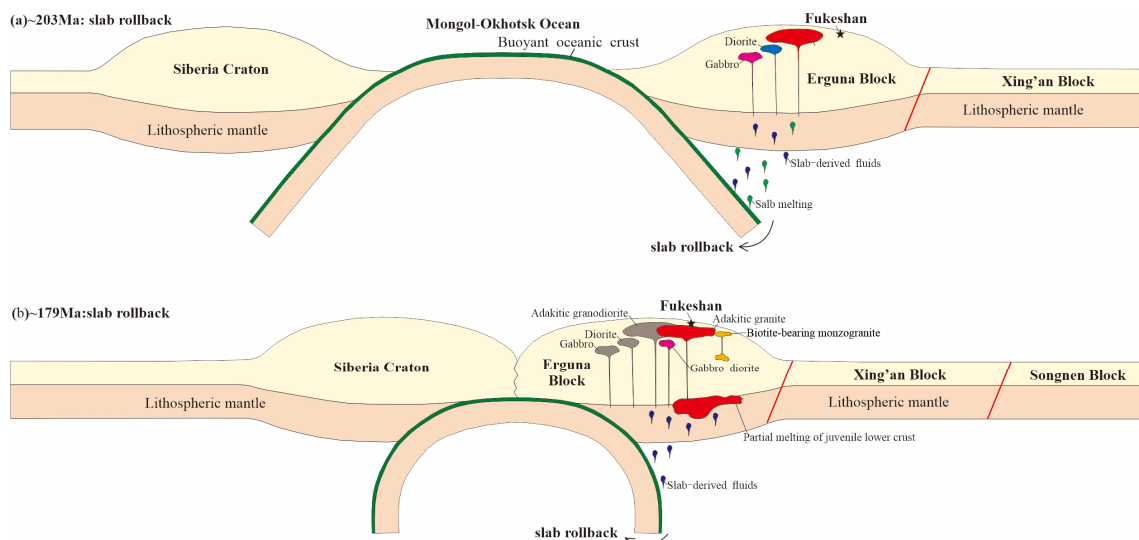


Figure 14. Schematic geodynamic model showing the tectonic setting and crust–mantle processes in the Fukeshan area of the northern Great Xing'an Range during the Late Triassic and the late Early Jurassic. (a) Late Triassic; (b) late Early Jurassic.

7. Conclusions

This study investigated late Early Jurassic magmatic rocks in the Fukeshan area of the northern Greater Khingan Range, providing critical insights into the tectonic evolution associated with the southward subduction of the Mongol–Okhotsk Ocean (MOO). The following key conclusions are drawn:

- (1) The magmatic rocks consist of gabbro, gabbro-diorite, granodiorite, porphyritic monzogranite, and biotite-bearing monzogranite, exhibiting typical continental arc characteristics.
- (2) The geochemical and isotopic data indicate that the mafic rocks were derived from partial melting of the lithospheric mantle, metasomatized by slab-derived fluids and sediment melts.
- (3) The granodiorite and porphyritic monzogranites, showing adakitic signatures, originated from the melting of a thickened lower crust. By contrast, the biotite-bearing monzogranites reflect a highly differentiated magma source derived from the middle to upper crust.
- (4) LA-ICP-MS zircon U–Pb dating reveals that the magmatic activity occurred between 183 and 179 Ma, coinciding with the active southward subduction of the MOO. This marks the final stage of subduction-related magmatism before transitioning into a syn-collisional regime during the Middle Jurassic.
- (5) The study highlights the role of high-angle subduction and slab rollback in driving extensive crust–mantle interactions. These processes include mantle wedge melt-

ing, magma underplating, and partial melting of crustal materials, resulting in the evolution of the continental magmatic arc.

- (6) The transition from arc magmatism to post-collisional tectonics marks the eventual closure of the MOO, contributing to crustal growth and tectonic reorganization in the region.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/min16030305/s1>, Table S1: Major (wt.%) and trace element data (ppm) for the Late Triassic–Early Jurassic intrusions in the Erguna Massif; Table S2: Zircon Hf isotopic data from the intrusives rocks in the Erguna Block.

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Conflicts of Interest: Wenlong Li, Chenglu Li, and Zhaoxun Cheng are employees of the Heilongjiang Institute of Natural Resources. Zhanlong Li is an employee of The Fifth Geological Exploration Institute of Heilongjiang Province. Masroor Alam is an employee of the Department of Earth Sciences, Karakoram International University. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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