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Jurassic Igneous Activity in the Yuseong Area on the Southern Margin of the Gyeonggi Massif, Korean Peninsula, and Its Implications for the Tectonic Evolution of Northeast Asia during the Jurassic

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Abstract: Jurassic dioritic to granitic igneous rocks extensively intrude into the southern Korean Peninsula, including the Yuseong area located at the boundary between the southern margin of the Gyeonggi Massif and the northern margin of the Okcheon Belt. In this study, the petrogenesis and sources of Jurassic igneous rocks in the Yuseong area were investigated. The U–Pb zircon age data from the Jurassic plutonic rocks in the Yuseong area give two igneous ages, ca. 178–177 Ma and 169–168 Ma, indicating that two stages of igneous activity occurred in the Yuseong area during the Jurassic. The geochemical characteristics of Jurassic diorites indicate that they originated from enriched mid-ocean ridge basalt (E-MORB; Nb/Yb = 5.63–7.27; Zr/Yb = 118–156). The enriched Th/Yb ratios (5.5–8.0) in the diorites imply that they experienced crustal contamination during magma ascent. The Jurassic granitoids in the Yuseong area are divided into I- and S-type granites. The Jurassic I-type granitoids may have formed via the partial melting of mafic rocks with mixtures of 10–40% pelite-derived melt, while the S-type granites originated from felsic pelite. The Jurassic diorites have low Nb/Th ratios with depletion of the Nb and Ta components, indicating that they formed in a volcanic arc tectonic environment. On the other hand, the Jurassic granitoids show two different tectonic environments: a volcanic arc, and a syncollisional environment. The granites with syncollisional character are S-type granites, and may give incorrect information about tectonic setting because of the changes in the trace elements of the S-type granite due to fractional crystallization. Early Jurassic (200–190 Ma) igneous rocks are distributed only in the southeastern Korean Peninsula, including the Yeongnam Massif; Jurassic igneous rocks formed at ca. 190–180 Ma occur mainly in the Okcheon Belt and southern Gyeonggi Massif, which includes the Yuseong area. Middle Jurassic igneous rocks widely intruded from the Okcheon Belt, through the Gyeonggi and Nangrim massifs in the Korean Peninsula, to the Liaoning area in the North China Craton at 180–160 Ma. This distribution pattern of the Jurassic granitoids suggests that flat subduction started after 180 Ma in Northeast Asia.

Keywords: Jurassic; flat subduction; igneous activity; Korean Peninsula; North China Craton

1. Introduction

In Northeast Asia, Mesozoic igneous rocks, including Jurassic granitoids, are widely distributed. Therefore, it is important to study Jurassic igneous activities in the Korean Peninsula in order to understand the tectonic evolution of the Korean Peninsula and Northeast Asia during the Jurassic Period. According to previous studies on the Jurassic granitoids in the Korean Peninsula: (1) the igneous rocks that formed during ca. 200–190 Ma are mainly distributed in the Yeongnam Massif (YM); (2) the magmatic front during ca. 190–180 Ma was located in the YM, but the distribution area of ca. 190–180 Ma igneous

rocks expanded northwards to the northern boundary of the Okcheon Belt; (3) the magmatic front during ca. 180–170 Ma moved northwards to the southern margin of the Okcheon Belt, and ca. 180–170 Ma igneous rocks are widely distributed from the Okcheon Belt through the Gyeonggi Massif to the Nangrim Massif in the Korean Peninsula; and (4) the magmatic front during ca. 170–160 Ma moved northwards again to the northern margin of the Okcheon Belt, with a wide distribution of ca. 170–160 Ma igneous rocks in the Korean Peninsula located to the north of the Okcheon Belt [1–5]. This distribution pattern of Jurassic igneous rocks implies that the igneous rocks in the boundary between the Okcheon Belt and the Gyeonggi Massif are important for interpreting the Jurassic geotectonic evolution of the Korean Peninsula. Several studies on the Jurassic igneous rocks in and around the Okcheon Belt have been conducted [1–3,5], and it has been suggested that the Jurassic igneous rocks in the Okcheon Belt formed via the partial melting of mantle sources, instead of the melting of mafic lower crust or oceanic crust [1,3]. However, there are no studies on the Jurassic igneous rocks in the Yuseong area, which are located in the boundary between the Okcheon Belt and the Gyeonggi Massif. Furthermore, there are no sufficient petrological studies on the Jurassic igneous rocks in and around the Okcheon Belt, such as studies on the source material, or the effects of crustal contamination and fractional crystallization. The petrogenesis of the S-type granite in the Okcheon Belt also has not been studied in detail.

Based on the spatial distribution patterns of the ages of Jurassic igneous rocks in the Korean Peninsula and their geochemical data, several tectonic evolutions of the Korean Peninsula during the Jurassic have been suggested [1,2,6]. However, those interpretations did not sufficiently consider the Jurassic igneous rocks in the northern Korean Peninsula, Japan, and northeastern China. It is difficult to understand the Jurassic tectonic evolution of Northeast Asia by using petrological studies on only the Jurassic igneous rocks in the Korean Peninsula. There have been many studies on Jurassic igneous rocks in the North China Craton (NCC) and Japan [7–13]. Therefore, it is necessary to interpret the tectonic evolution of Northeast Asia during the Jurassic period by combining petrological studies on the Korean Peninsula with those in the NCC and Japan.

Therefore, in this study, four Jurassic granitoids and two Jurassic diorites were collected from the Yuseong area, located at the boundary between the Okcheon Belt and the Gyeonggi Massif (Figure 1a), and zircon U–Pb dating was conducted using laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) to identify the intrusion time. The whole-rock major and trace element geochemistry of the Jurassic igneous rocks in the Yuseong area were also investigated so as to understand their petrogenesis and tectonic setting. Finally, the regional tectonic evolution of Northeast Asia during the Jurassic will be discussed by combining petrological studies on Jurassic igneous rocks in the Korean Peninsula, NCC, and Japan.

2. General Geology and Petrography

The basement of the Korean Peninsula is composed of four main Precambrian massifs: the Kwanmo, Nangrim, Gyeonggi, and Yeongnam massifs, from north to south. The Macheonryeong system and Imjingang Belt are located between the Kwanmo and Nangrim massifs and between the Nangrim and Gyeonggi massifs, respectively [14]. The Okcheon Belt is located between the Gyeonggi Massif and the YM, and divided into the Okcheon Metamorphic Belt and the Taebaeksan Basin. The Okcheon Metamorphic Belt is a fold and thrust belt, with a northeastern trend mainly composed of Neoproterozoic metamorphosed volcano-sedimentary rocks and Paleozoic metasedimentary rocks, while the Taebaeksan Basin consists of Paleozoic sedimentary rocks [1,2,15]. The Permo–Triassic collision event between the NCC and the South China Craton may have triggered the beginning of the subduction zone in which the Paleo-Pacific plate subducted beneath the Northeast Asian plate along the southeastern margin of Northeast Asia, which includes the southern margin of the South China Craton and the YM in the Korean Peninsula [16,17]. According to previous studies, the Jurassic igneous rocks in the South China Craton formed due to

subduction of the Paleo-Pacific plate beneath the South China Cratons [18–21]. In particular, Zhou and Li (2000) [20] suggested that the wide distribution of Mesozoic igneous rocks in southeastern China was caused by low-angle subduction of the Paleo-Pacific plate. The Jurassic igneous rocks in northeast China are also considered to have formed via flat subduction on the Paleo-Pacific plate [13,22]. The Jurassic plutons in southwestern Japan also intruded in a subduction tectonic setting [23,24], and Japan was connected to the Korean Peninsula during the Jurassic. Egawa (2013) [23] noted that the several Jurassic basins in the Korean Peninsula were developed via thrust movement with crustal shortening, caused by flat subduction of the Paleo-Pacific plate beneath the Northeast Asian continent. Thus, these previous studies indicate that the subduction zone was developed along the eastern margin of Northeast Asia, including the Korean Peninsula. These subduction-related arc igneous activities also occurred in the Korean Peninsula, and continued until the Middle Jurassic, ca. 160 Ma [3,12]. The Late Triassic and Early Jurassic igneous rocks mainly intruded in the YM and Okcheon Belt, whereas Middle Jurassic igneous rocks are widely distributed not only in the Okcheon Belt and the Gyeonggi Massif in the southern Korean Peninsula, but also in the northern Korean Peninsula and northeastern NCC [1,3,10–12,25,26].

The Triassic igneous rocks in the YM include alkali granite, hornblende–biotite granodiorite, and biotite granite, and they are considered to have intruded in an arc tectonic environment [1,11]. The Jurassic igneous rocks are mainly diorite, granodiorite, two-mica granite, and biotite granite with small diorite enclaves [2,3,12]. Some igneous rocks intruded during the Triassic and Early Jurassic have foliated textures formed by right-lateral strike-slip movement along the Honam shear zone [2,27,28]. The Honam shear zone is considered a dextral ductile shear zone forming several mylonite zones [1,29]. The right-lateral movement of the Honam shear zone may have started from 180–178 Ma, based on zircon overgrowth ages of 180–178 Ma using sensitive high-resolution ion microprobe (SHRIMP) U–Pb analysis [30].

The study area in Yuseong is located at the boundary between the Gyeonggi Massif and the Okcheon Belt in the southern Korean Peninsula (Figure 1a). The basement rocks in the Yuseong area mainly consist of Paleoproterozoic biotite gneiss and schist. The Paleozoic metasedimentary rocks unconformably overlie the basement, and are composed of mica schist and quartzite. The study area was intruded by Mesozoic igneous rocks such as diorite, biotite granite, two-mica granite, and granophyre (Figure 1b). Most Mesozoic granitoids are Jurassic granitoids that are medium- to coarse-grained, and consist of quartz, plagioclase, alkali feldspar, biotite, and muscovite, with fewer opaque minerals. Some granitoids include alkali feldspar megacrysts or small-scale mafic enclaves. The diorite is almost medium-grained, and is composed mainly of plagioclase, amphibole, biotite, and alkali feldspar.

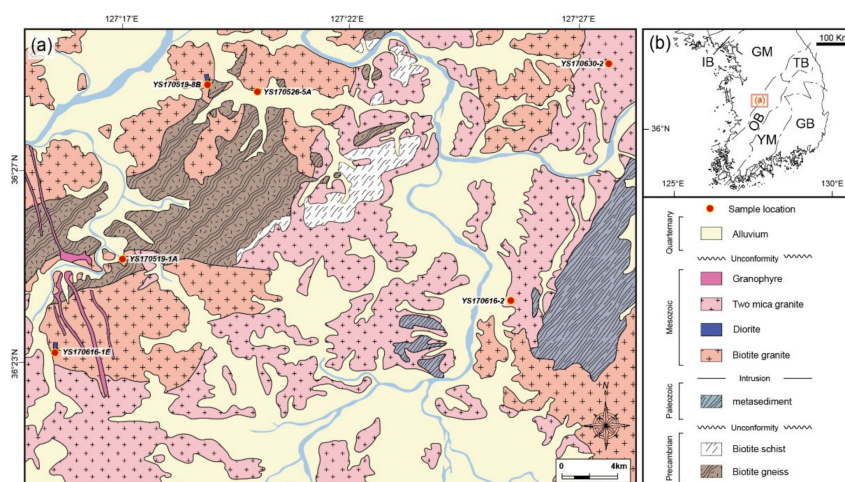


Figure 1. (a) Geological map of the Yuseong area (after, Park and Lee, [26]). (b) Simplified tectonic map of the southern Korean Peninsula. Abbreviations are as follows, GM: Gyeonggi Massif; YM: Yeongnam Massif; IB: Imjingang Belt; OB: Okcheon Belt; TB: Taebaeksan Basin; GB: Gyeongsang Basin.

3. Analytical Methods

The Jurassic granitoids and diorite collected from the Yuseong area were crushed to the point at which 90% passed through a 10-mesh sieve, and were then split to yield ~250 g samples. Each split sample was pulverized to the point at which 95% passed through a 200-mesh sieve, in order to provide a homogeneous and representative sample for analysis. The whole-rock major and trace element chemistries of the Jurassic granitoids and diorites were analyzed using inductively coupled plasma atomic emission spectroscopy (ICP-AES; Termo Jarrel Ash ENVIRO II) and inductively coupled plasma mass spectrometry (ICP-MS; Perkin Elmer Optima 3000) at Activation Laboratories Ltd., Ancaster, Canada. The results are shown in Table 1.

Table 1. Whole-rock composition of the Jurassic diorite and granite in the Yuseong area.

Rock Type	Diorite		Granitoids			
sample	YS170519-8B	YS170616-1B	YS170526-5A	YS170630-2	YS170616-2	YS170519-1A
Major element (wt%)						
SiO ₂	58.72	60.87	67.72	73.83	74.69	69.30
Al ₂ O ₃	14.99	14.79	16.26	14.56	14.86	15.56
MnO	0.09	0.08	0.03	0.12	0.05	0.06
MgO	5.86	4.04	0.43	0.10	0.09	0.68
CaO	5.65	4.63	1.11	0.49	0.65	3.44
Fe ₂ O ₃ ^t	6.33	5.01	2.36	1.37	1.05	3.61
Na ₂ O	3.15	3.30	4.66	3.62	3.37	3.61
K ₂ O	2.94	3.45	5.10	4.42	5.01	2.67
TiO ₂	0.87	0.67	0.32	0.07	0.03	0.34
P ₂ O ₅	0.24	0.19	0.10	0.08	0.06	0.11
LOI	1.55	2.83	0.86	0.83	0.55	0.60
Total	100.40	99.87	98.94	99.48	100.40	99.98
Mg#	0.51	0.47	0.17	0.08	0.09	0.17
A/CNK	0.80	0.84	1.07	1.25	1.22	1.03
Trace element (ppm)						
Sc	16.00	12.00	2.00	2.00	1.00	3.00
Cr	380.00	260.00	110.00	140.00	110.00	<20
Zn	90.00	70.00	< 30	60.00	50.00	80.00
Ga	19.00	19.00	20.00	28.00	25.00	22.00
Rb	78.00	109.00	197.00	415.00	375.00	134.00
Sr	492.00	520.00	272.00	58.00	30.00	523.00
Y	17.00	13.00	9.00	19.00	23.00	14.00
Zr	189.00	172.00	202.00	51.00	41.00	197.00
Nb	9.00	8.00	14.00	30.00	28.00	23.00
Cs	2.40	1.90	3.60	12.20	6.00	2.70
Ba	945.00	1143.00	950.00	188.00	70.00	1077.00
La	36.40	33.10	58.60	12.60	9.50	41.80
Ce	69.70	61.00	108.00	27.20	19.20	78.60
Pr	7.73	6.62	10.90	2.79	2.21	8.42
Nd	28.10	23.60	36.10	9.50	7.50	30.30
Sm	5.30	4.20	5.90	2.50	2.60	5.50
Eu	1.36	1.20	0.92	0.20	0.14	1.29
Gd	4.30	3.40	3.60	2.30	3.00	3.90
Tb	0.60	0.50	0.40	0.50	0.60	0.60
Dy	3.20	2.60	2.00	3.40	3.90	3.00
Ho	0.60	0.50	0.40	0.60	0.70	0.50
Er	1.70	1.30	0.90	1.70	1.90	1.50
Tm	0.26	0.18	0.11	0.27	0.33	0.20
Yb	1.60	1.10	0.60	1.90	2.30	1.30
Lu	0.24	0.17	0.10	0.32	0.36	0.20

Table 1. Cont.

Rock Type	Diorite		Granitoids			
Hf	4.10	4.20	4.90	2.20	2.30	4.50
Ta	0.60	0.60	1.90	8.20	7.00	2.10
Pb	12.00	19.00	30.00	37.00	41.00	18.00
Th	8.80	8.80	30.60	10.30	8.00	8.40
U	1.70	1.90	5.90	10.90	4.80	1.80
Eu/Eu*	0.87	0.97	0.61	0.25	0.15	0.85
(Th/Yb) _{PM}	30.51	44.38	282.91	30.07	19.29	35.84
(Nb/Yb) _{PM}	3.77	4.87	15.64	10.58	8.16	11.86
(La/Yb) _N	15.45	20.44	66.35	4.50	2.81	21.84
T _{Zr} (°C)	-	-	924.42	788.97	770.20	921.62

A/CNK = molar Al₂O₃/(CaO + Na₂O + K₂O), Mg# = molar Mg²⁺/(Mg²⁺ + Fe²⁺) × 100, Eu/Eu* = Eu_N/√Sm_N × Gd_N, T_{Zr} values are calculated after Watson and Harrison (1983) [31].

The zircon grains were separated using standard crushing, water-based panning, magnetic separation, and heavy liquid techniques, in order to analyze the U–Pb isotopic composition of zircon in the Jurassic granite and diorite. The separated zircon grains were handpicked and mounted with standard zircons of 91,500 (1062.6 ± 1.2 Ma) and Plesovice (337.6 ± 0.69 Ma) in an epoxy disk. The internal textures of the zircon grains were examined by cathodoluminescence (CL) images obtained using scanning electron microscopy with a JEOL JSM–6610 LV instrument. The in situ zircon ages were analyzed by LA-MC-ICP-MS at the Ohchang Center, Korea Basic Science Institute (KBSI), with a Nu Plasma II MC-ICP-MS and a NWR193UC (193 nm) laser ablation system. Mean ²³⁸U/²⁰⁶Pb ages of the Jurassic zircons were calculated by assuming that the analyses were concordant. Common Pb was removed via the ²⁰⁷Pb correction method, using the model used by Stacy & Kramers (1975) [32]. The zircon U–Pb age data are summarized in Tables S1 and S2.

4. Results

4.1. Geochronology

The zircons in diorite YS170616-1E are 100–200 µm in grain size, with length to width ratios of approximately 1:1 to 3:1. These zircons show mostly rounded and elongated shapes with banded and concentric zoning patterns, representing their igneous origin. Some zircons have inherited cores. The igneous zircons from this diorite (YS170616-1E) provide a weighted mean ²³⁸U/²⁰⁶Pb age of 177.3 ± 1.5 Ma (n = 16, mean square weighted deviation (MSWD) = 4.0) (Figure 2a). Two inherited cores give concordant Paleoproterozoic (2286 Ma) and Triassic (242 Ma) ages. The zircons in diorite YS170519-8B are 60–200 µm in grain size, with length to width ratios of approximately 1:1 to 2:1. These zircons show mostly angular and rounded shapes with banded and concentric zoning patterns, representing their igneous origin. This diorite (YS170519-8B) gives a weighted mean intrusion age of 168.8 ± 4.4 Ma (n = 5, MSWD = 1.9) (Figure 2b). Some zircons include inherited cores with concordant Paleoproterozoic (1848–1795 Ma, n = 4) ages.

The zircons in granitoid YS170519-1A have mostly small to medium grain sizes of 50–200 µm, with length to width ratios of approximately 1:1 to 3:1. They show mostly rounded or prismatic shapes with banded and concentric zoning patterns, indicating their igneous origin. The zircons in this granitoid give a weighted mean ²³⁸U/²⁰⁶Pb age of 178.4 ± 1.7 Ma (n = 21, MSWD = 4.1) (Figure 2c). The zircons in granitoid YS170526-5A have mostly small to medium grain sizes of 30–200 µm, with length to width ratios of approximately 1:1 to 3:1. They show mostly rounded or prismatic shapes with banded and concentric zoning patterns, indicating their igneous origin. The zircons from this granitoid give a weighted mean ²³⁸U/²⁰⁶Pb intrusion age of 168.8 ± 0.3 Ma (n = 24, MSWD = 0.1) (Figure 2d).

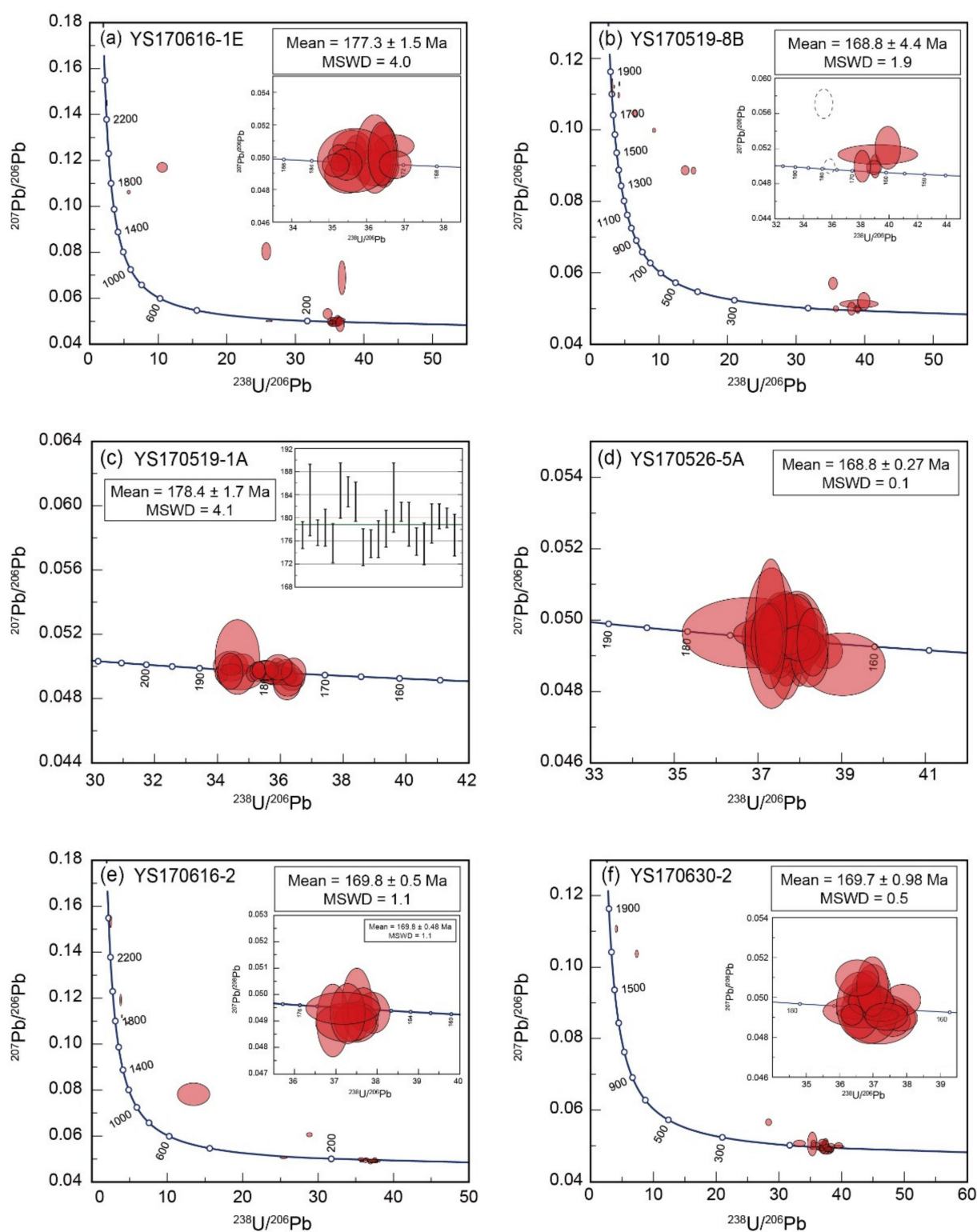


Figure 2. Zircon U-Pb concordia diagrams for (a,b) the Jurassic diorite, and (c–f) granitoids in the Yuseong area.

The zircons in granitoid YS170616-2 have mostly small to medium grain sizes of 100–150 μm , with length to width ratios of approximately 1:1 to 3:1. They show mostly rounded or prismatic shapes with banded and concentric zoning patterns, representing their igneous origin, and some of them have inherited zircons. The zircons from this granite (YS170616-2) give a weighted mean $^{238}\text{U}/^{206}\text{Pb}$ intrusion age of 169.8 ± 0.5 Ma ($n = 13$, MSWD = 1.1) (Figure 2e). The inherited cores give concordant Paleoproterozoic (2188 Ma) and Triassic (248 Ma) ages. The zircons in granitoid YS170630-2 have mostly small to medium grain sizes of 30–200 μm , with length to width ratios of approximately 1:1 to 4:1. They show mostly rounded or prismatic shapes with banded and concentric zoning patterns, representing their igneous origin, and some of them have inherited zircons. The zircons from this granite (YS170630-2) give a weighted mean $^{238}\text{U}/^{206}\text{Pb}$ intrusion age of 169.7 ± 1.0 Ma ($n = 18$, MSWD = 0.5) (Figure 2f). There are several inherited cores that give discordant ages with expected Precambrian ages.

The age dating results of the diorites and granitoids in the Yuseong area indicate that there were two magmatic stages: ca. 177–178 Ma, and ca. 168–169 Ma.

4.2. Whole-Rock Geochemistry

The Jurassic diorites in the Yuseong area in the boundary between the Okcheon Belt and the Gyeonggi Massif have geochemical characteristics comparable to typical diorite compositions (Figure 3a; $\text{SiO}_2 = 58.7\text{--}60.9$ wt%, $\text{Na}_2\text{O} + \text{K}_2\text{O} = 6.1\text{--}6.8$ wt%). The granitoid that formed at 178 Ma plots in the granodiorite field area ($\text{SiO}_2 = 69.3$ wt%, $\text{Na}_2\text{O} + \text{K}_2\text{O} = 6.3$ wt%), and the other granitoids that formed at 169 Ma plot in the quartz monzonite and granite field areas ($\text{SiO}_2 = 67.7\text{--}74.7$ wt%, $\text{Na}_2\text{O} + \text{K}_2\text{O} = 8.0\text{--}9.8$ wt%) (Figure 3a). On the other hand, the Early Jurassic (200–190 Ma) igneous rocks in the YM reported by Kee et al. [1] and Kim et al. [30] plot in the fields of gabbro, gabbroic diorite, diorite, granodiorite, syenite, and granite. All Jurassic igneous rocks in the Yuseong area are calc-alkaline series in the AFM diagram, and they plot in the high-K calc-alkaline series—except for the 178 Ma granodiorite, which shows a medium-K calc-alkaline series in the SiO_2 vs. K_2O diagram (Figure 3b,c). The Early Jurassic igneous rocks in the YM plot in the medium-K to high-K calc-alkaline series, and one of them plots in the shoshonitic series field. All Jurassic granitoids in the Yuseong area show peraluminous character, whereas Early Jurassic granitoids plot in the metaluminous and peraluminous fields in the A/CNK vs. A/NK diagram (Figure 3d).

The Jurassic igneous rocks in the Yuseong area are plotted in several tectonic discrimination diagrams, together with Early Jurassic igneous rocks in the YM, to investigate the tectonic setting of Jurassic igneous activities. The Jurassic diorite in the Yuseong area has Nb/Th and Zr/Nb ratios comparable to those of typical arc-related basalt, implying a volcanic arc tectonic setting, and plots in the arc-basalt and calc-alkaline basalt (CAB) fields in the Hf/3-Th-Ta diagram, together with the Early Jurassic mafic igneous rocks (Figure 4a,b). Specific trace element ratios—such as Zr/Yb, Nb/Yb, and Y/Yb ratios—of the diorites in the Yuseong area and the mafic to intermediate igneous rocks in the YM are comparable to those of enriched mid-oceanic ridge basalt (E-MORB) (Figure 4c,d).

The Jurassic granitoids in the Yuseong area plot in the volcanic arc granite (VAG) or syncollisional granite (Syn-COLG) fields in the Rb vs. Y + Nb diagram (Figure 5a). On the other hand, all Jurassic granitoids in the Yuseong area correspond to the typical igneous rocks formed in an arc-related tectonic setting, based on the Zr vs. Y diagram (Figure 5b). Two different tectonic settings for the granites in the Rb vs. Y + Nb diagram will be further discussed in the discussion in Section 5.2. The Early Jurassic granitoids in the YM plot mostly in an arc tectonic setting in the above two diagrams, but some of them plot in the syncollisional granite field in the Rb vs. Y + Nb diagram, and in the within-plate field in the Zr vs. Y diagram. The Middle Jurassic granitoids in the southern Korean Peninsula also show mostly typical arc signatures, but some of them plot in the syncollisional and within-plate granite fields in the Rb vs. Y + Nb diagram. The Middle Jurassic granitoids, including the Yuseong Jurassic granitoids, plot in the I-, S-, M-, and A-type granite fields in

the $K_2O + Na_2O$ vs. $10,000Ga/Al$ and Nb vs. $10,000Ga/Al$ diagrams, and they plot in the fractionated I- and S-type granite fields in the Zr vs. $10,000Ga/Al$ diagram (Figure 5c–e). The Early Jurassic granitoids in the YM plot mostly in the normal I-, S-, and M-type fields, and some of them plot in the A-type field (Figure 5c–e). The granodiorite that formed at 178 Ma, along with one of the 168 Ma granitoids which plots in the quartz monzonite field, plot in the I-type granite field area in the A/CNK vs. SiO_2 diagram, and two granites that formed at 168 Ma plot in the S-type granite field (Figure 5f). All of the Early Jurassic granitoids are distributed in the I-type granite field area, whereas the Middle Jurassic granitoids in the southern Korean Peninsula plot both in the I-type and S-type granite fields as the Yuseong Jurassic granitoids (Figure 5e,f).

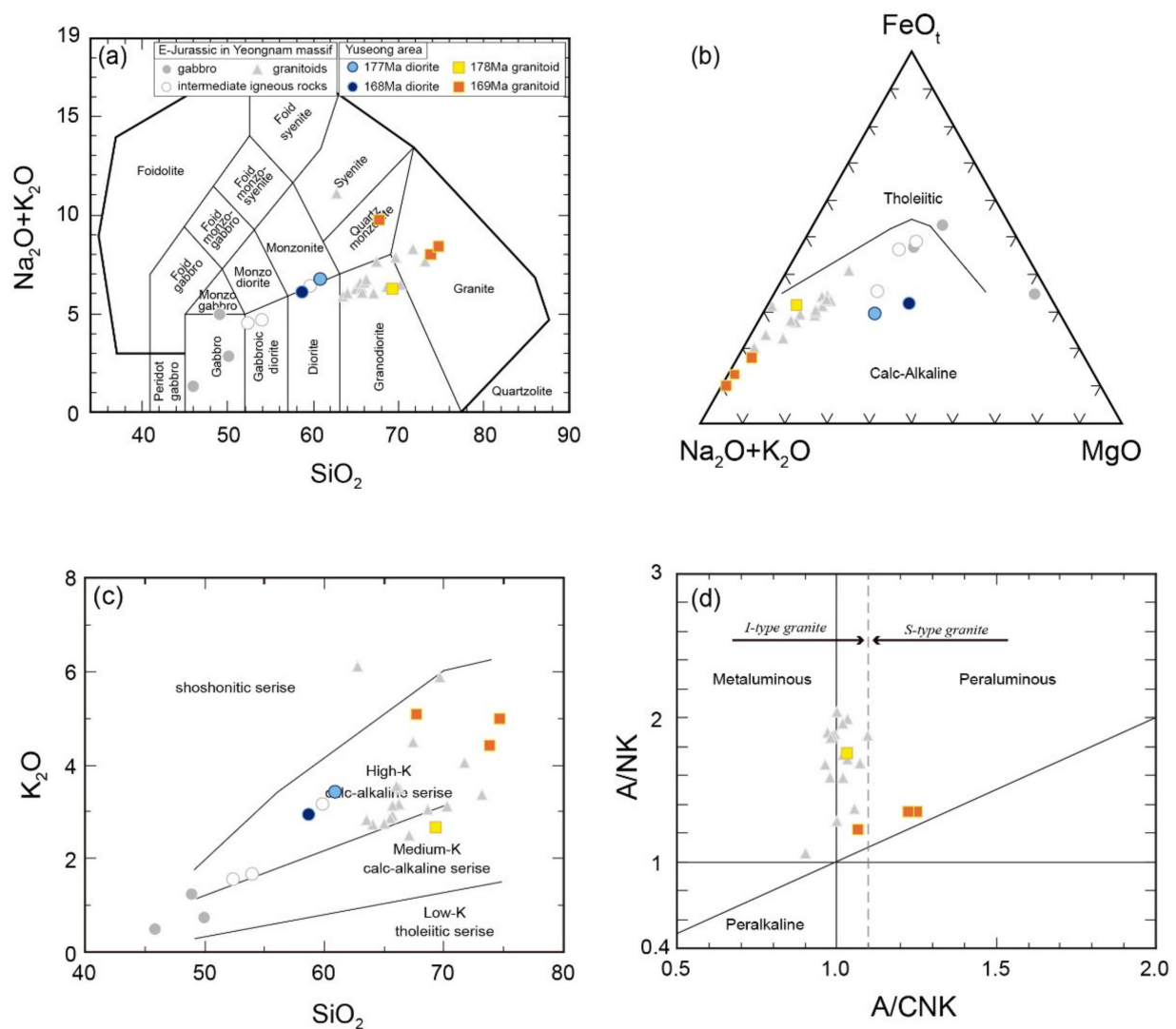


Figure 3. Chemical classification using major elements of the Jurassic diorite and granitoids in the Yuseong area together with Early Jurassic igneous rocks in the YM in the (a) total alkali ($Na_2O + K_2O$) vs. silica (SiO_2) diagram (after Middlemost [33]), (b) FeO_t - $Na_2O + K_2O$ - MgO diagram (after Irvine and Baragar [34]), (c) K_2O vs. SiO_2 diagram (after Peccerillo and Taylor [34,35]), and (d) A/NK vs. A/CNK diagram (after Maniar and Piccoli, [36]). E-Jurassic: Early Jurassic. Data sources of Early Jurassic igneous rock in the YM are from Kee et al. [1] and Kim et al. [3].

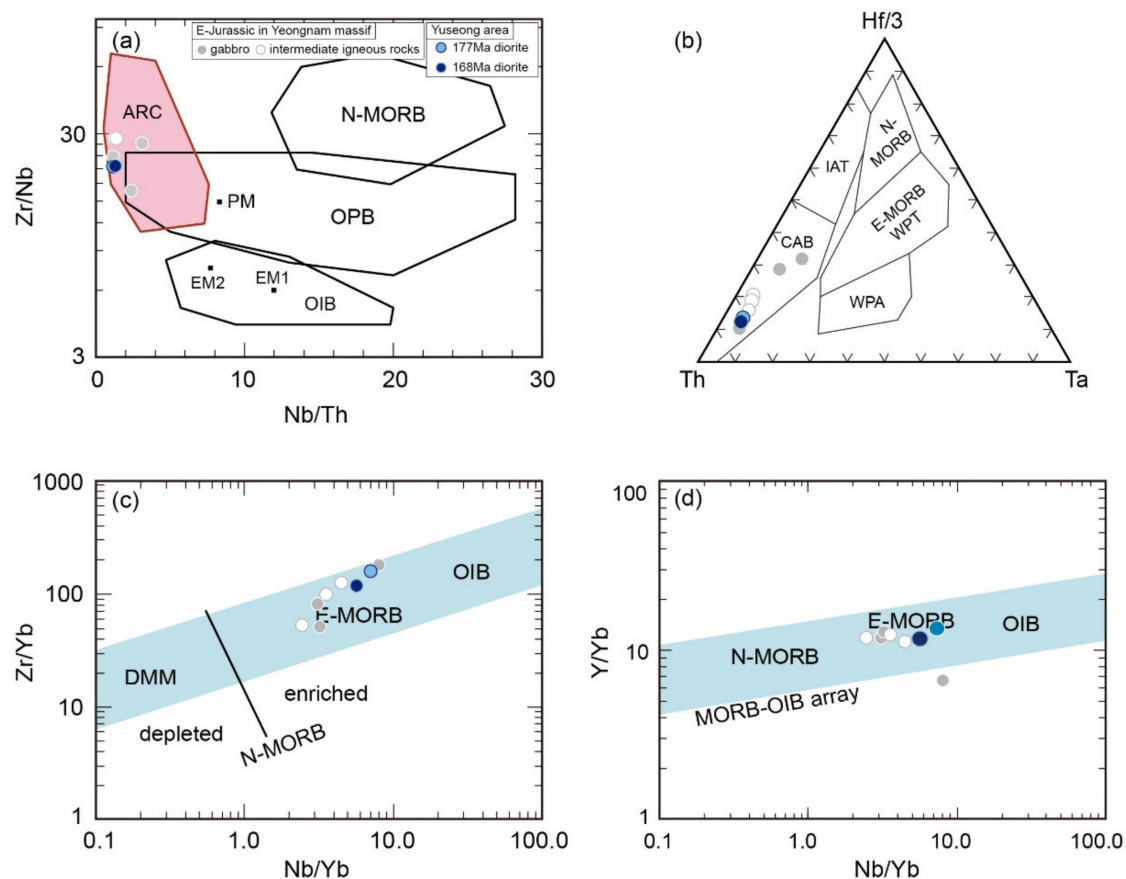


Figure 4. Variation plots for the Middle Jurassic diorite in the Yuseong area and the Early Jurassic gabbro and intermediate igneous rocks in the YM in the (a) Zr/Nb vs. Nb/Th (after Condie [27]), (b) Hf/3-Th-Ta (after Wood [37]), (c) Zr/Yb vs. Nb/Yb, and (d) Y/Yb vs. Nb/Yb (after Green [38]) diagrams. ARC: arc related basalt; PM: primitive mantle; OPB: ocean plateau basalt; N-MORB: normal mid-oceanic ridge basalt; EM1: enriched mantle 1; EM2: enriched mantle 2; OIB: ocean island basalt; CAB: calc-alkaline basalt; IAT: island-arc tholeiite; E-MORB: enriched mid-oceanic ridge basalt; WPT: within-plate tholeiite; WPA: within-plate alkaline basalt; DMM: depleted MORB mantle.

All Jurassic igneous rocks in the Yuseong area show enrichment in light rare-earth elements (LREEs) and depletion in heavy rare-earth elements (HREEs) ($(La/Yb)_N = 2.8\text{--}66.3$) in the C1 chondrite-normalized REE diagram (Figure 6a,c). The Jurassic diorites in the Yuseong area and the gabbro and intermediate igneous rocks in the YM show negative Nb and Ta anomalies, with moderate negative Ti anomalies in the primitive mantle-normalized spider diagram (Figure 6b). The early Jurassic gabbro in the YM shows more depleted character than the diorite (Figure 6a,b). In the primitive mantle-normalized diagram, the I-type granitoids in the Yuseong area show weaker negative anomalies of Nb than do the Early Jurassic granites in the YM (Figure 6d). Compared with the I-type granitoids in the Yuseong area and the YM, granites with S-type characteristics in the Yuseong area have strong negative Eu anomalies in the chondrite-normalized REE diagram, and stronger negative Ba and Ti anomalies in the primitive mantle-normalized diagram. The Middle Jurassic granitoids show stronger negative anomalies of Eu and Ti, and weaker negative anomalies of Nb and Ta components, compared with the Early Jurassic granitoids (Figure 6c,d).

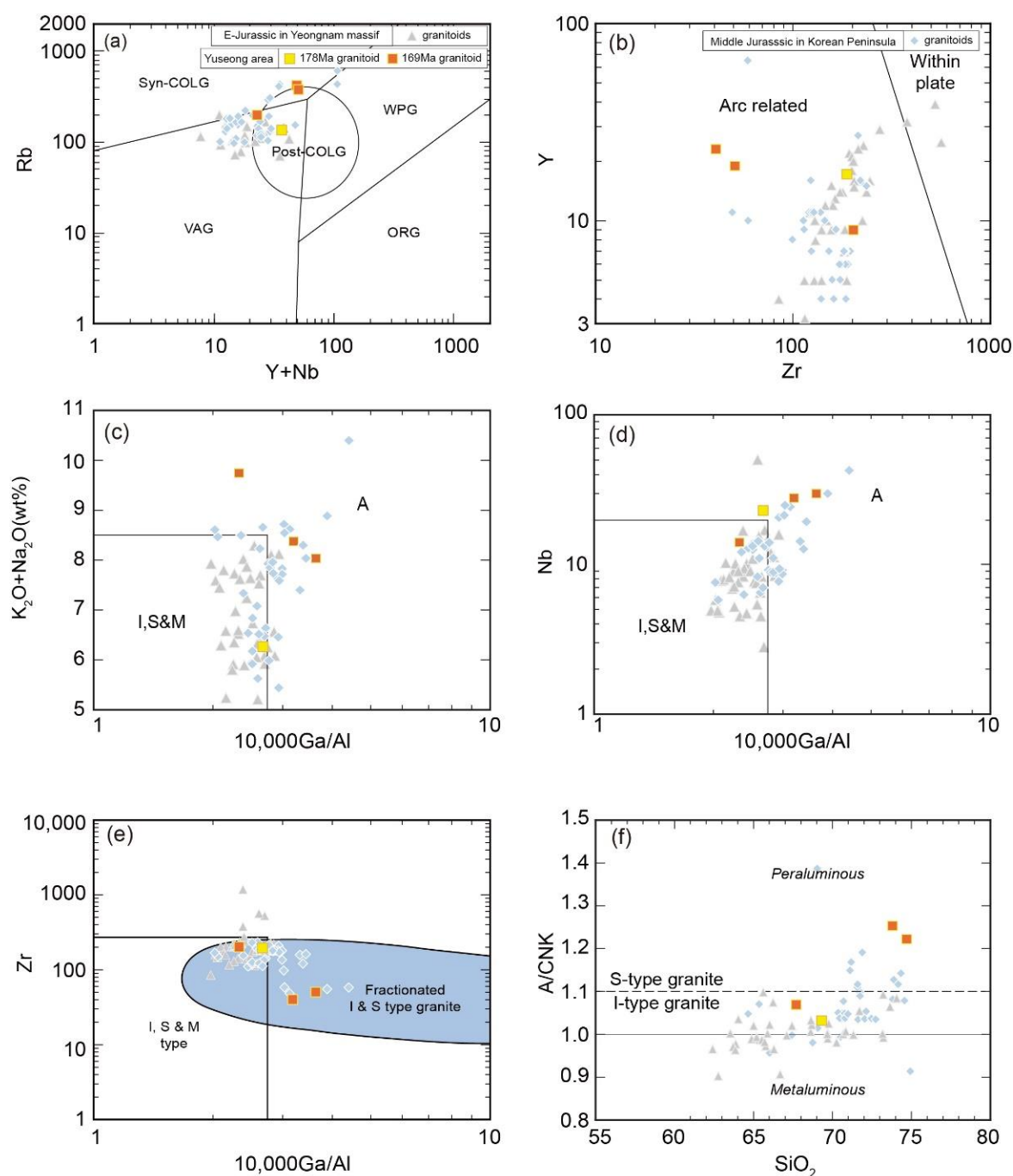


Figure 5. Binary plots for the Middle Jurassic granitoids in the Yuseong area and Early Jurassic granitoids in the YM in the (a) Rb vs. Y + Nb (after Pearce et al. [39]), (b) Y vs. Zr (after Müller et al. [40]), (c) $K_2O + Na_2O$ vs. $10,000Ga/Al$ (after Whalen et al. [41]), (d) Nb vs. $10,000Ga/Al$ (after Whalen et al. [41]), (e) Zr vs. $10,000Ga/Al$ (after Wu et al. [42]), and (f) A/CNK vs. SiO_2 (after Maniar and Piccoli [36]) diagrams. Data sources of Middle Jurassic granitoids in Korean Peninsula from Kim et al. (2015) [3] and references therein.

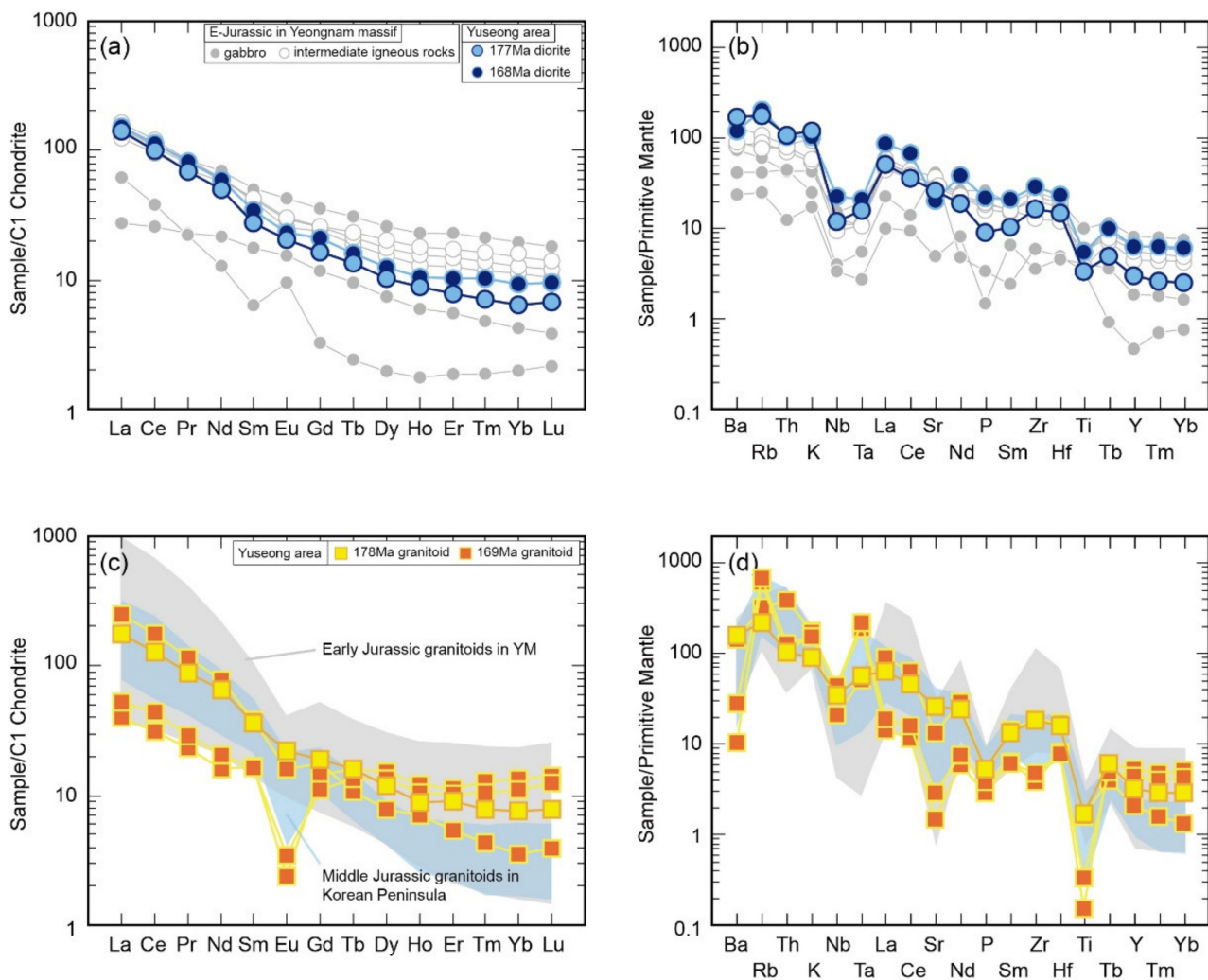


Figure 6. Chondrite-normalized REE and primitive mantle-normalized multi-element patterns for the Early Jurassic gabbro and intermediate igneous rocks in the YM and Jurassic diorite in the Yuseong area (a,b) and for the Early Jurassic granitoids in the YM, Jurassic granitoids in the Yuseong area and Middle Jurassic granitoids in the Korean Peninsula (c,d). Chondrite- and primitive mantle-normalized values are from McDonough and Sun [43].

5. Discussion

5.1. Petrogenesis of the Jurassic Diorite in the Yuseong Area and the YM

The Jurassic diorites in the Yuseong area display high-K calc-alkaline characteristics (Figure 3b,c). Their Nb/Th and Zr/Nb characteristics are comparable to those of igneous rocks formed in an arc tectonic setting (Figure 4a), and enrichments in large-ion lithophile elements (LILEs; e.g., Rb and Ba), along with significant depletions in high-field-strength elements (HFSEs)—such as Nb and Ta—also indicate an arc tectonic environment [1,44]. These Jurassic diorites have higher Mg# ($\text{Mg\#} = \text{molar Mg}^{2+} / (\text{Mg}^{2+} + \text{Fe}^{2+}) \times 100$) (47–50) and MgO (4.0–5.9 wt%) contents than those in the typical melt from mafic lower crust, implying their origin from the mantle instead of the crust [45,46] (Figure 7a,b). In the Zr/Yb vs. Nb/Yb and Y/Yb vs. Nb/Yb diagrams, including the mid-ocean ridge basalt (MORB) array, the Jurassic diorite shows enriched characteristics, with an E-MORB-like signature instead of normal mid-ocean ridge basalt (N-MORB) or ocean island basalt (OIB) characteristics (Figure 4c,d). In particular, the higher Nb/Yb (5.6–7.3) and Zr/Yb (118–156) ratios in the diorite, compared with those of depleted asthenosphere-derived magma (N-MORB) (Nb/Yb = 0.8, Zr/Yb = 24.3; McDonough and Sun [43]), suggest that the diorite did not originate from depleted asthenospheric mantle. The early Jurassic gabbro and intermediate igneous rocks in the YM show trace element characteristics similar to those in

the Yuseong area, such as Zr/Nb , Nb/Th , Zr/Yb , Y/Yb , and Nb/Yb ratios, and they are also considered to have formed via the melting of enriched mantle sources [1,3].

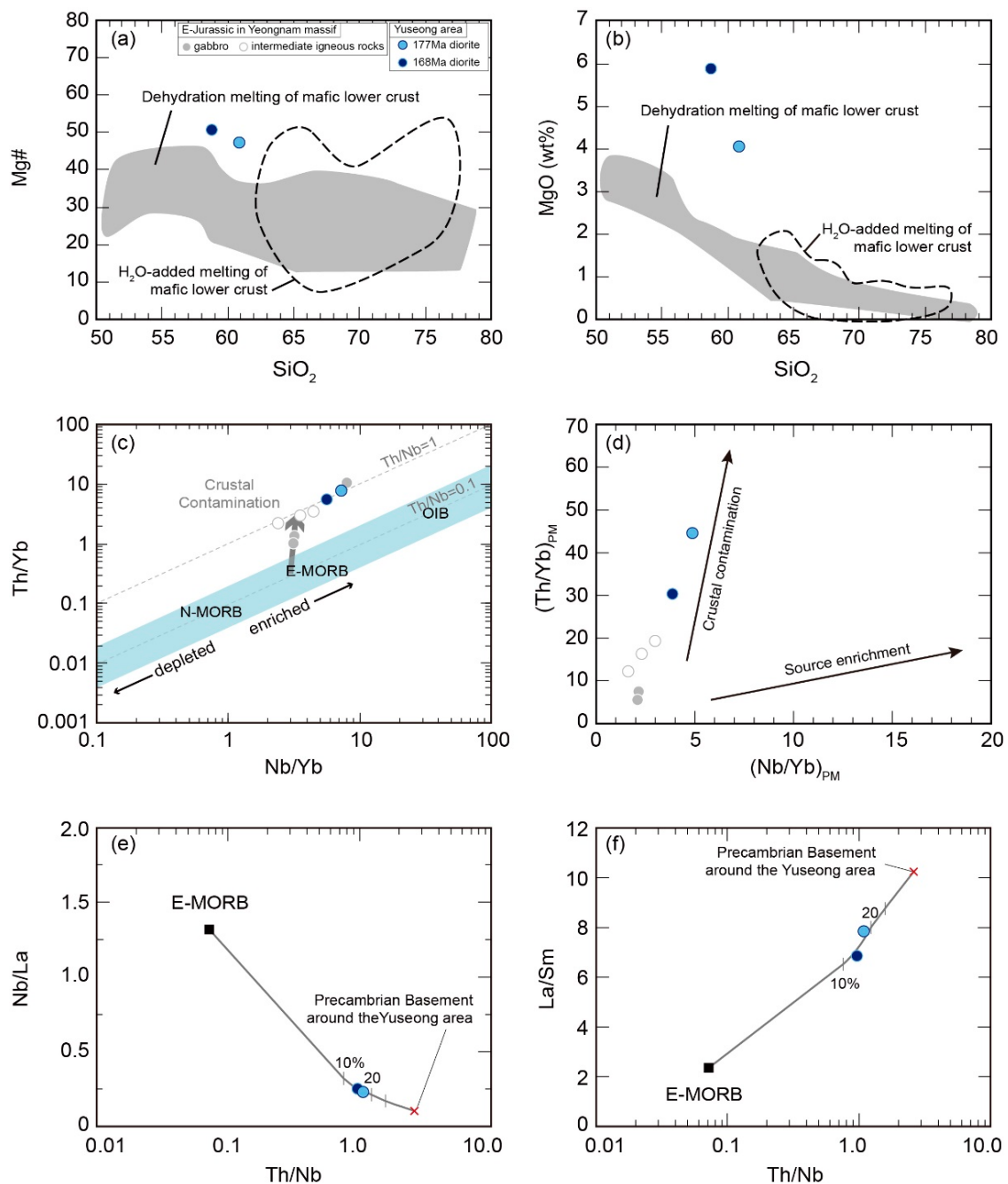


Figure 7. Binary plots for the Jurassic diorite in the Yuseong area and the Early Jurassic gabbro and intermediate igneous rocks in the YM in the (a) $Mg\#$ vs. SiO_2 , (b) MgO vs. SiO_2 (after Lu et al. [47]), (c) Th/Yb vs. Nb/Yb , (after Green [38]) (d) $(Th/Yb)_{PM}$ vs. $(Nb/Yb)_{PM}$ (after Jowitt and Ernst [48]), (e) Nb/La vs. Th/Nb , and (f) La/Sm vs. Th/Nb diagrams.

The $(Th/Yb)_{PM}$ vs. $(Nb/Yb)_{PM}$ diagram is used to investigate whether magma underwent crustal contamination or source enrichment [48]. Distinctly higher $(Th/Yb)_{PM}$ values than $(Nb/Yb)_{PM}$ values ($(Th/Yb)_{PM} = 30.5\text{--}44.3$, $(Nb/Yb)_{PM} = 3.7\text{--}4.8$) in the diorite indicate that the enrichment occurred due to crustal contamination during magma ascent (Figure 7d). In the Th/Yb vs. Nb/Yb diagram (Figure 7c), the Jurassic diorite plots above the MORB array, with high Th/Yb ratios of 5.5–8.0, which also supports the significant crustal contamination of source magma. Additionally, the existence of inherited zircons

showing Paleoproterozoic ages in the diorite also indicates crustal assimilation. The early Jurassic gabbro and intermediate igneous rocks in the YM also show elevated Th/Yb and $(\text{Th}/\text{Yb})_{\text{PM}}$ ratios, implying crustal contamination, but they do not seem to have experienced a high degree of contamination, because their $(\text{Th}/\text{Yb})_{\text{PM}}$ values are lower than 20. To calculate the degree of crustal contamination for the diorites in the Yuseong area, mass balance modeling was carried out using the trace element ratios of possible contaminants and primary magma sources. Most enriched Paleoproterozoic gneisses in the southern Gyeonggi Massif reported by Lee et al. [49] were chosen as possible contaminants because they were expected to be basement rocks in the Yuseong area, and the E-MORB component suggested by McDonough and Sun [43] was chosen as the source material. The results show that the Jurassic diorite in the Yuseong area formed from an E-MORB-like enriched mantle source, with 10–20% crustal assimilation by Paleoproterozoic gneiss (Figure 7e,f). The Jurassic diorite in the Yuseong area also shows relatively high Ce/Th (6.9–7.9) and Ba/Th (107–130) ratios, which are similar to those of subducted sediment-derived melts (Ce/Th = ~8, Ba/Th = ~111; Plank and Langmuir [50]), suggesting that the source magma of Jurassic diorite underwent metasomatism caused by subducted sediment-derived melt or fluid. Therefore, it is difficult to exclude a minor effect of mantle metasomatism during the formation of the diorite.

5.2. Petrogenesis of the Jurassic Granite in the Yuseong Area and YM

In the $10,000\text{Ga}/\text{Al}$ vs. Zr diagram, Jurassic granitoids in the Yuseong area have geochemical characteristics of I- and S-type granites with different degrees of fractionation. They are further classified in the A/CNK vs. SiO_2 diagram (Figure 3d). The granitoids in the Yuseong area with A/CNK values of 1.22–1.25 are classified as S-type granites, but other granitoids with A/CNK values of 1.03–1.07 can be classified as I-type granites.

The difference in trace element patterns between the I- and S-type granitoids in the Yuseong area also supports their different origins. Strong negative anomalies of Ba, Eu, Sr, and Ti components in the trace element patterns are observed in the S-type granites, suggesting that the magma for S-type granites underwent fractional crystallization of plagioclase-, K-feldspar-, and Ti-bearing oxide minerals (Figure 6c,d). On the other hand, I-type granitoids in the Yuseong area do not show depletions in Eu or Sr, and show weak negative anomalies of P and Ti. These features suggest that the I-type granitoids in the Yuseong area experienced no fractional crystallization of feldspars, and weak fractional crystallization of P- and Ti-bearing oxides, such as amphibole and garnet. In the C1 chondrite-normalized REE diagrams, the I-type granitoids show more enrichment of LREEs and depletion of HREEs than the S-type granites.

The chemical differences between I- and S-type granitoids in the Yuseong area may be attributed not only to fractional crystallization, but also to different sources. To identify the source material of the Jurassic granitoids in the Yuseong area, they were plotted in the $\text{CaO}/\text{Al}_2\text{O}_3$ vs. $\text{CaO} + \text{Al}_2\text{O}_3$ and Rb/Ba vs. Rb/Sr diagrams. The S-type granites in the Yuseong area plot in the felsic pelite source field, and their high Rb/Sr and Rb/Ba ratios also suggest that they formed via the melting of plagioclase-poor and clay-rich pelites (Figure 8a,b).

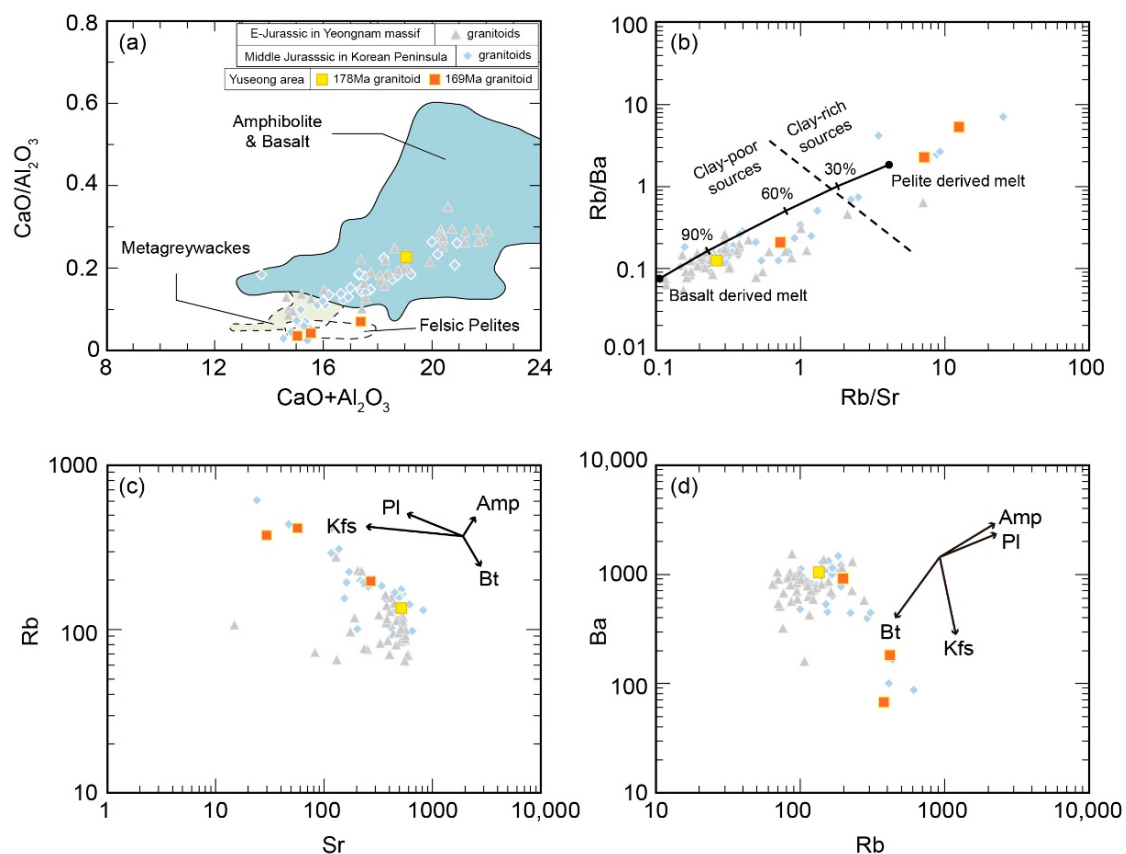


Figure 8. Binary plots for the Middle Jurassic granitoids in the Yuseong area, Early Jurassic granitoids in the YM, and Middle Jurassic granitoids in the Korean Peninsula in the (a) $\text{CaO}/\text{Al}_2\text{O}_3$ vs. $\text{CaO} + \text{Al}_2\text{O}_3$ (after Douce [51]), (b) Rb/Ba vs. Rb/Sr (after Douce and Harris [52], Sylvester [53]), (c) Rb vs. Sr , and (d) Ba vs. Rb diagrams. The mineral fractionation paths are calculated using the mineral/melt partition coefficient suggested by Hanson [54]. Pl: plagioclase; Kfs: K-feldspar; Amp: amphibole; Bt: biotite.

Generally, I-type granitoids can be formed via the partial melting of both mantle and lower crust [55–57], and fractional crystallization of mantle-derived magmas during the underplating process [58,59]. The Mg# values of I-type granitoids (16–17) in the Yuseong area show crustal-like signatures, because these values are significantly lower than the mantle composition (40; Rapp and Watson [60]). In the $\text{CaO}/\text{Al}_2\text{O}_3$ vs. $\text{CaO} + \text{Al}_2\text{O}_3$ diagram, the 179 Ma granodiorite—which is one of the I-type granitoids in the Yuseong area—plots in the amphibolite and basalt source field, while the 168 Ma quartz monzonite showing I-type characteristics plots in the areas between the amphibolite and basalt source field and the felsic pelite source field (Figure 8a). In the Rb/Sr vs. Rb/Ba diagram, the I-type granitoids in the Yuseong area can be considered to have formed via mixing between basaltic-derived melt and pelite-derived melt; the mixing percentages of melt from basalts are approximately 90% and 60%, for the 179 Ma granodiorite and the 168 Ma quartz monzonite, respectively (Figure 8b). These data indicate that the I-type Jurassic granitoids in the Yuseong area formed from basalt-derived melt that was mixed with 10–40% magma derived from pelites. The crystallization temperature of the I-type granitoids was estimated to be 922–924 °C, based on the calculation of zircon saturation temperature suggested by Watson and Harrison [31]. These calculated crystallization temperatures would also support the melting of mafic rocks. The Early Jurassic granitoids in the YM mostly originated from basalt-derived melt with 10–40% mixing of pelite-derived melt, and only a few granitoids originated from pelite or metagraywacke compositions, whereas the Middle Jurassic granitoids, including the Yuseong Jurassic granitoids in the southern Korean Peninsula, originated from both basaltic-derived melt and felsic pelite- or clay-rich-material-derived melt (Figure 8a,b). The

changes in specific trace elements that indicate fractional crystallization, such as Rb and Ba, are not as noticeable in the Early Jurassic granitoids in the YM, compared with the Jurassic granitoids in the southern Korean Peninsula, including the Yuseong area (Figure 8c,d). The tendency of C1 chondrite and primitive mantle-normalized trace element patterns is also different between the Early Jurassic granitoids and the Middle Jurassic granitoids (Figure 6). Furthermore, the Early Jurassic granitoids do not include S-type granites, but the Middle Jurassic granitoids do (Figure 5f). These geochemical characteristics of the Early Jurassic granitoids in the YM indicate that the Early Jurassic magmatism mainly formed via the melting of mafic lower crust instead of upper crust. On the other hand, the Middle Jurassic granitoids can be considered to have formed not only via the melting of mafic lower crust, but also via the melting of upper crust.

Based on the results in Sections 5.1 and 5.2, the following interpretations can be made: During the Early Jurassic, magma formed via the partial melting of mantle and of lower mafic crust, whereas during the Middle Jurassic, magma formed via the partial melting of mantle and of upper and lower crusts that had pelitic and mafic compositions, respectively. This difference indicates that there was more prolonged arc magmatism in the Yuseong area than in the YM due to flat subduction, which will be explained in the next section.

5.3. The Regional Evolution of the Subduction Process in Northeast Asia during the Jurassic

According to previous studies, it was reported that, along the margin of the Northeast Asia, including the Korean Peninsula, there was a subduction of the Paleo-Pacific plate during the Jurassic era. Park et al. (2019) [61] suggested that the Daebo Orogeny occurred via low-angle subduction of the Paleo-Pacific plate in the Korean Peninsula during the Jurassic, based on study of the structural and deformation age from the Mesozoic basin in the Korean Peninsula. The Early to Middle Jurassic igneous rocks which are widely distributed in the Korean Peninsula are also considered to have formed due to northwestern subduction of the Paleo-Pacific plate beneath Northeast Asia, based on their geochemical signature [1,3–6,12]. These Jurassic igneous rocks were divided into two groups based on their emplacement age and spatial distribution: Early Jurassic (ca. 200–180 Ma) igneous rocks are mainly distributed in the YM, the Okcheon Belt, and the eastern margin of the Korean Peninsula, while Early to Middle Jurassic (ca. 180–160 Ma) igneous rocks are widely distributed in the Okcheon Belt, the Gyeonggi and Nangrim massifs in the Korean Peninsula, and the northeastern part of the NCC [1,3–5,9–12,62]. Park et al. [4] suggested that the granite that formed at 190–180 Ma is concentrated in the Okcheon Belt and the southern Gyeonggi Massif, based on zircon U–Pb SHRIMP analysis and sphene U–Pb thermal ionization mass spectrometry (TIMS) analysis. Thus, the Jurassic igneous activities in the Korean Peninsula can be divided into three subgroups: (1) ca. 200–190 Ma igneous activity in the YM and the eastern margin of the northeastern Korean Peninsula; (2) ca. 190–180 Ma igneous activity in the Okcheon Belt, southern Gyeonggi Massif, and eastern margin of the Korean Peninsula; and (3) Middle Jurassic igneous activity at ca. 180–160 Ma in the Okcheon Belt, Gyeonggi Massif in the southern Korean Peninsula, and Nangrim Massif in the northern Korean Peninsula. The arc magmatic front was located in the YM during the Early Jurassic (ca. 200–180 Ma) and moved northward to the southern margin of the Okcheon Belt during ca. 180–170 Ma, and then to the northern margin of the Okcheon Belt during ca. 170–160 Ma (Figure 9). These spatial distributions of Jurassic igneous rocks represent a northwestward trend of becoming younger on the Korean Peninsula, and the distribution area of Jurassic igneous rocks increased with time. This pattern can be interpreted as a result of the decreasing subduction angle of the subducting Paleo-Pacific plate from the Early to Middle Jurassic, resulting in flat subduction during the Middle Jurassic [1,6,10,23]. Although various petrological studies of the Jurassic igneous rocks in the Korean Peninsula have been conducted as discussed above, several problems remain in interpreting the tectonic evolution of Northeast Asia during the Jurassic period.

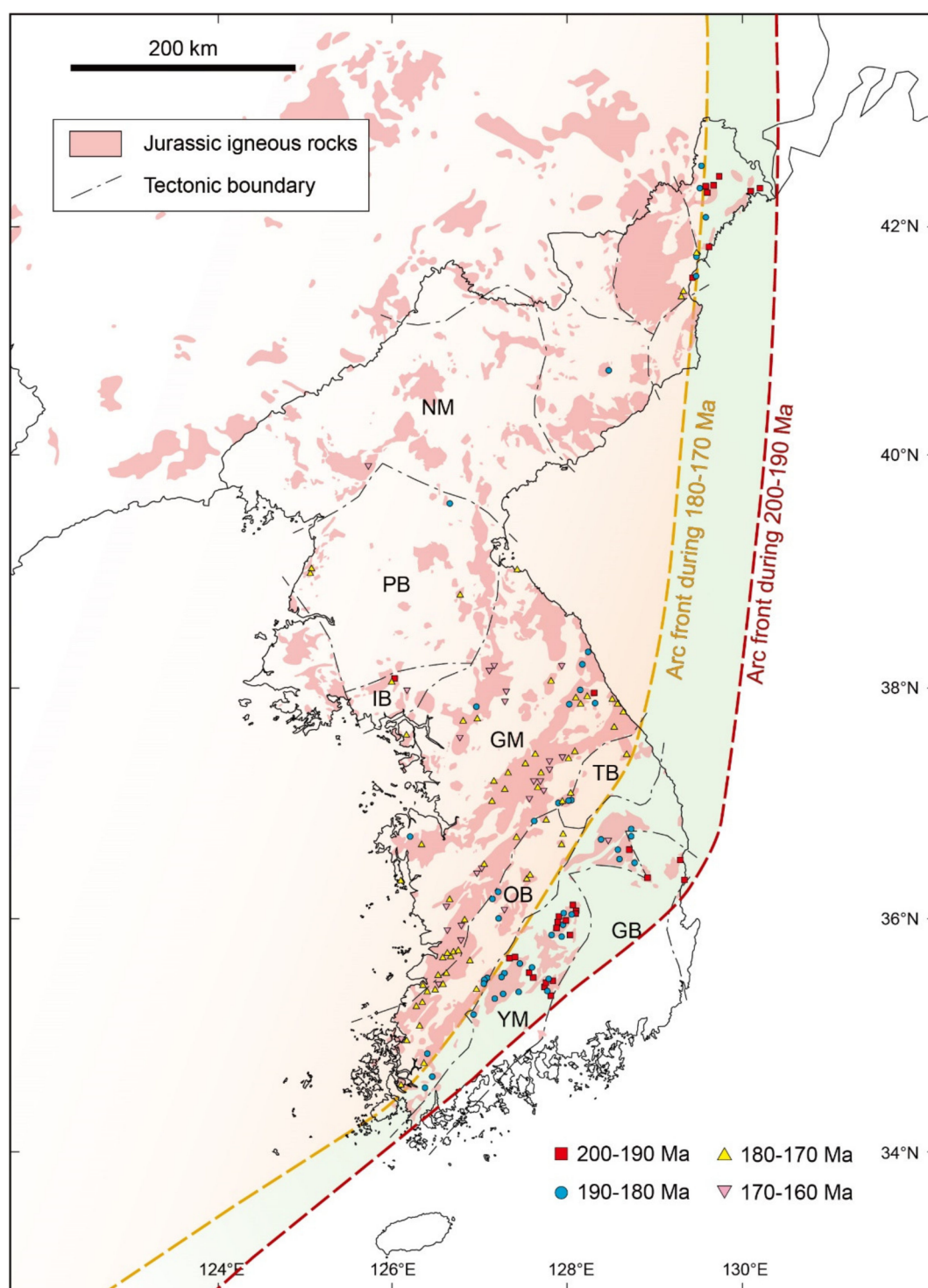


Figure 9. The map showing spatial distribution of the Jurassic igneous rocks in the Korean peninsula and northeastern China. Data sources are from [1–4,12]. The arc front was located in the YM during Early Jurassic (ca. 200–180 Ma) and moved northward to the southern margin of the Okcheon Belt during ca. 180–170 Ma, and then to the northern margin of the Okcheon Belt during ca. 170–160 Ma. NM: Nangrim Massif; PB: Pyeongnam Basin; IB: Imjingang Belt; GM: Gyeonggi Massif; OB: Okcheon Belt; TB: Taebaeksan Basin; YM: Yeongnam Massif; GB: Gyeongsang Basin.

Kee et al. [1] suggested inland propagation of the edge of the subducted plate, but they did not consider the Jurassic igneous rocks in the northern Korean Peninsula, NCC, or Japan. Cheong and Jo [6] reported that low-angle subduction of the Paleo-Pacific plate occurred during 190–170 Ma, and that the subduction angle became flat with the

termination of igneous activity in the Korean Peninsula during 170–160 Ma. However, the Jurassic igneous rocks that formed at 170–160 Ma occur widely in the Korean Peninsula and the northeastern part of the NCC [3,4,9,10,12,13]. Therefore, it is necessary to interpret the evolution of Jurassic subduction in the Korean Peninsula more clearly, by considering Jurassic igneous rocks in the northern Korean Peninsula and Northeast Asia, including the northeastern NCC and Japan.

In Japan, igneous activity occurred during the Early Jurassic period of ca. 197–180 Ma, forming granodiorite and biotite granite [7,8,63], and Jurassic igneous activity stopped after ca. 180 Ma. However, Middle to Late Jurassic (177–148 Ma) igneous rocks are reported in the Liaoning area on the northern margin of the NCC [11,64], and in the Beijing area, which is located west of the Liaoning area [25,62]. The presence of Middle Jurassic age data in the eastern NCC indicates that ca. 177–160 Ma igneous activity occurred not only in the Korean Peninsula, but also in the eastern NCC. The Jurassic igneous activities in the Korean Peninsula finished at approximately 160 Ma, whereas they continued until ca. 148 Ma in the Liaoning area [25,62], and until ca. 140 Ma in the area near Beijing.

These data indicate that: (1) the subduction angle of the Paleo-Pacific plate under Northeast Asia decreased continuously from 200 Ma to 180 Ma (Figure 10a,b), (2) flat subduction started from ca. 180 Ma, resulting in igneous activity throughout the Korean Peninsula and the northeastern NCC during 180–160 Ma (Figure 10c), and (3) the edge of subducted flat slab moved northwestward from the Korean Peninsula to the NCC, arriving in the Liaoning area at 148 Ma, and finally the Beijing area at 140 Ma, and igneous activity occurred only at the Liaoning and Beijing areas in the NCC, which are at the edge of the subducted flat slab with no magmatism in the Korean peninsula, due to the cooling of the subducted flat slab (Figure 10d). In the Beijing area, Early Cretaceous magmatism ca. 136 Ma occurred due to mantle uplift, which was caused by extension-related slab rollback. Cretaceous magmatism due to slab rollback propagated southeastwards in Northeast Asia, occurring from 122 Ma in the Liaoning area and from 110 Ma and 90 Ma in the northwestern and southeastern Korean Peninsula, respectively.

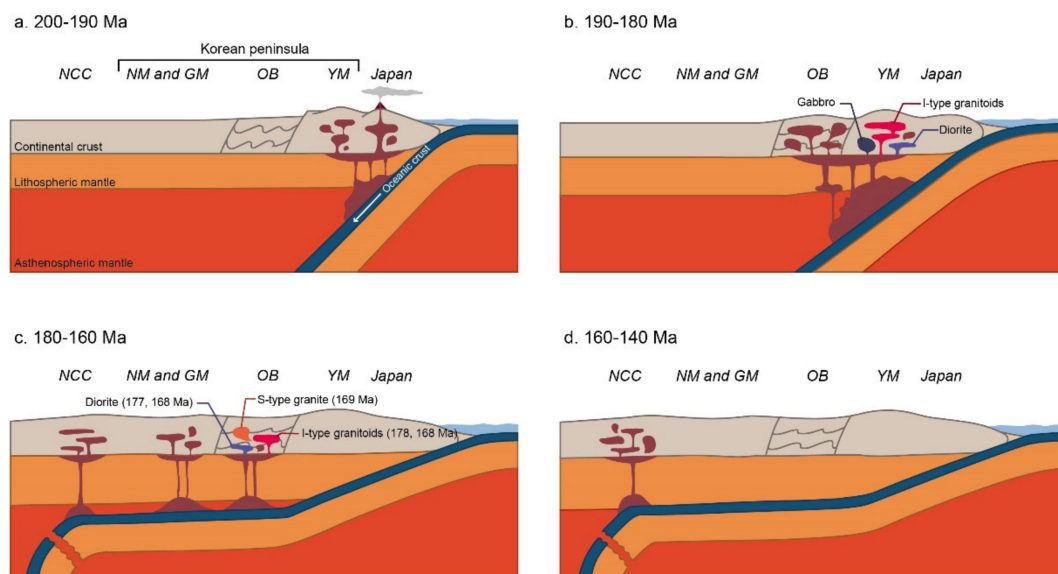


Figure 10. Tectonic evolution model during Jurassic period in the northeastern Asian continent, including the Korean Peninsula and the northeastern part of the North China Craton (NCC). (a) 200–190 Ma: Arc-related igneous activities in Japan and the Yeongnam massif in the Korean peninsula. (b) 190–180 Ma: Igneous activities in the YM and OB, with no magmatism in Japan, due to migration of the arc front into the southern margin of the Okcheon Belt in the Korean Peninsula. (c) 180–160 Ma: Igneous activities in the OB, GM, and NM in the Korean Peninsula and the NCC, due to the flat subduction of the Paleo-Pacific plate. (d) 160–140 Ma: Igneous activities in the NCC until 140 Ma with no magmatism in the Korean peninsula, due to the cooling of the subducted flat slab. The abbreviations of tectonic units are explained in Figure 9.

Wu et al. [10] also reported that the northwestern younging trend of Jurassic magmatism finished around the Beijing area at 140 Ma, and that a reverse younging trend toward the southeast started from the Beijing area during the Cretaceous. Their interpretation suggests that the Jurassic flat subduction of the Paleo-Pacific plate continued until the edge of the flat subduction reached the Beijing area, and then the reverse younging trend of Cretaceous magmatism was caused by slab rollback of the flat subducted Paleo-Pacific plate. As a result, the magmatic gap increases southeastwards as the distance from the Beijing area increases; the magmatic gap in the Liaoning area is 148–126 Ma [11], and that in the Korean Peninsula is 160–110 Ma.

The Yuseong area is located at the boundary between the Okcheon Belt and the Gyeonggi Massif, which can be considered an arc front during flat subduction. As a result, igneous activity continued for a long time from 178 Ma to 168 Ma. During the early igneous stage, diorite and I-type granitoids intruded, whereas during the later igneous stage, diorite, I-type granitoids, and S-type granite intruded. The S-type granite can be interpreted as having formed due to prolonged arc activity, which finally caused melting of the upper crust.

6. Conclusions

- (1) The Jurassic igneous rocks in the Yuseong area consist of diorite and granitoids, and they formed at 177–178 Ma and 168–169 Ma, indicating that there were two stages of igneous activity in the Yuseong area during the Jurassic.
- (2) The Jurassic diorite has geochemical characteristics that are representative of a volcanic arc tectonic setting. The geochemical characteristics of the Jurassic granitoids indicate two tectonic environments: a volcanic arc, and a syncollisional environment. The syncollisional character is not correct because it resulted from strong fractionation of plagioclase and alkali feldspar from the parental magma, which formed in a volcanic arc tectonic setting. These data indicate that the Jurassic igneous rocks in the study area intruded in an arc tectonic setting.
- (3) The Jurassic diorites originated from an E-MORB-type mantle source, and have relatively high Th/Yb ratios of 8.0–5.5, indicating that they underwent 10–20% crustal contamination during magma ascent. The Jurassic I-type granodiorite that formed at 178 Ma originated from basalt-derived melt, with 10% mixing of pelite-derived melt, and the I-type quartz monzonite that intruded at 168 Ma formed from basalt-derived melt that mixed with approximately 40% pelite-derived melt. The Jurassic S-type granite in the Yuseong area was formed from a pelite-derived melt source.
- (4) Flat subduction began to occur at 175 Ma under the northern Asian continent, and continued until 140 Ma.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/min11050466/s1>, Table S1: LA-MC-ICPMS zircon ages of the Jurassic diorite in the Yuseong area, Table S2: LA-MC-ICPMS zircon ages of the Jurassic granitoids in the Yuseong area.

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Data Availability Statement: All data analyzed during this study are included in this published article [Table 1, Supplementary Tables S1 and S2].

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

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