Article

Identification and Geological Significance of Early Jurassic Adakitic Volcanic Rocks in Xintaimen Area, Western Liaoning

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Abstract: The Western Liaoning area, where a large number of Jurassic-Cretaceous volcanic rocks are exposed, is one of the typical areas for studying the Mesozoic Paleo-Pacific and Mongolia-Okhotsk subduction process, and lithospheric destruction of North China Craton. The identification and investigation of Early Jurassic adakitic volcanic rocks in the Xintaimen area of Western Liaoning is of particular significance for exploring the volcanic magma source and its composition evolution, tracking the crust-mantle interaction, and revealing the craton destruction and the subduction of oceanic plates. Detailed petrography, zircon U–Pb dating, geochemistry, and zircon Hf isotope studies indicate that the Early Jurassic intermediate-acidic volcanic rocks are mainly composed of trachydacites and a few rhyolites with the formation ages of 178.6–181.9 Ma. Geochemical characteristics show that they have a high content of SiO₂, MgO, Al₂O₃, and total-alkali, typical of the high-K calc-alkaline series. They also show enrichment of light rare earth elements (LREEs) and large ion lithophile elements (LILEs), depletion of heavy rare earth elements (HREEs) and high field strength elements (HFSEs), and have a high content of Sr and low content of Y and Yb, suggesting that they were derived from the partial melting of the lower crust. The $\epsilon_{\text{Hf}}(t)$ values of dated zircons and two-stage model ages (T_{DM2}) vary from −11.6 to −7.4 and from 1692 to 1958 Ma, respectively. During the Early Jurassic, the study area was under long-range tectonic effects with the closure of the Mongolia-Okhotsk Ocean and the subduction of the Paleo-Pacific plate, which caused the basaltic magma to invade the lower crust of the North China Craton. The mantle-derived magma was separated and crystallized while heating the Proterozoic lower crust, and part of the thickened crust melted to form these intermediate-acidic adakitic volcanic rocks.

Keywords: adakite; zircon U–Pb age; North China Craton; Western Liaoning; Paleo-Pacific plate

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1. Introduction

Adakite has attracted much attention due to its unique magma source, geodynamic significance, and close relationship with metal deposits. The term “adakite” originally refers to a set of intermediate-acidic igneous rocks formed by slab melting in the subduction environment, with geochemical characteristics of MgO ≤ 3 wt.%, SiO₂ ≥ 56 wt.%, Al₂O₃ ≥ 15 wt.%, La/Yb ≥ 20, Sr/Y ≥ 40, and/or low Y ≤ 18 ppm [1–4]. However, some intermediate-acidic igneous rocks with the geochemical characteristics of adakite are not necessarily developed in an island arc environment or by the melting of subducted slabs [5–11]. These rocks are collectively referred to as adakitic rocks. In this study, a set of intermediate-acidic adakitic volcanic rocks with high-K calc-alkaline series affinity were

identified in the Western Liaoning area, which is located on the northern margin of the North China Craton (NCC; Figure 1).

As one of the oldest cratons in the world, the NCC has a long history of ~3.8 billion years, which preserves a relatively complete tectonic evolution that contains metamorphic basement from Archean to Paleoproterozoic and Phanerozoic caprock development (Figure 1) [12–19]. The Western Liaoning is located in the northern margin of the NCC and the eastern part of the Yanshan tectonic belt which developed a large number of Mesozoic volcanic-sedimentary basins with lots of lacustrine paleontological fossils. Therefore, Western Liaoning is one of the classic areas to study the Mesozoic tectonic-magma and biological evolution in the NCC (Figures 1 and 2) [6,18,20–26].

Figure 1. Simplified map showing the tectonic subdivisions of the North China Craton and the distribution of the basement rocks (modified after Zhao et al. [13]; NCC for North China Craton, SCC for South China Craton).

Since the Mesozoic, the Western Liaoning region was affected by the superimposition of the NE trending Paleo-Pacific plate tectonic domain, Mongolia-Okhotsk tectonic domain and the nearly EW trending Central Asian Orogenic Belt (CAOB). In complex tectonic regimes, the wide development of Mesozoic volcanic rocks began in the Early Jurassic and ended in the late Early Cretaceous. Geochronology of the Mesozoic volcanic events in the Western Liaoning region have been studied in detail by predecessors, which can be divided into four phases: Early Jurassic (Nandaling or Xinglonggou Period), Late Jurassic (Tiaojishan or Lanqi Period), Early Cretaceous (Zhangjiakou or Yixian Period), and Late Cretaceous (Daxingzhuang Period) [6,24,27–37]. However, most of the geochronological and biological studies focused on the Late Jurassic–Early Cretaceous magmatic events, and most scholars believed that the Late Jurassic magmatic rocks may be the result of the Paleo-Pacific subduction [6,20,21] or the combined influence of the subduction and closure of the Mongolia-Okhotsk Ocean [38–40]. The widely distributed Early Cretaceous magmatic rocks were formed under a strong extensional background, which was related to the subduction of the Paleo-Pacific plate [20,21,25,26,40,41]. However, the distribution and tectonic setting of the Early Jurassic volcanic rocks are still controversial [6,36,37,39,42,43].

A wide range of volcanic rocks was exposed in the Xintaimen area, Western Liaoning region, but the only research was mostly focused on the Yanliao biota and Jehol biota which occur in this area [44–47], and their ages were roughly defined as the middle and late Early Cretaceous. However, detailed fieldwork has found that the large-scale Early Jurassic adakitic volcanic rocks now identified in the Western Liaoning region, previously were rarely reported and were included in the middle and late Early Cretaceous biota divisions. This paper conducts a systematic study on the Early Jurassic volcanic rocks, including petrology, geochemistry, zircon U-Pb chronology, and Lu-Hf isotope analysis, and then discusses its magma origin, petrogenesis, and crust-mantle interaction, all of which provide a key position and important window for understanding the subduction process of the Paleo-Pacific plate and the superposition, conversion, and transformation of different tectonic regimes (Figure 1) [48–51].

Figure 2. Geological map of Western Liaoning province (a); modified after Lin [52] and distribution of Early Jurassic volcanic rocks with sampling locations (b). Note: The rectangle (b) in Figure 2a shows the location of Figure 2b. Figure 2a shows a traditional understanding of the basin distribution, Figure 2b shows the volcanic rocks based on new-age data. Therefore, the area displayed as green in Figure 2a becomes blue in Figure 2b.

2. Geological Setting

The northern boundary of NCC is the Central Asian Orogenic Belt, adjacent to the Siberian Craton, and its eastern edge is connected with the Pacific plate, and its southern boundary is the Qinling-Dabie-Sulu ultrahigh-pressure belt, adjacent to the South China Craton (Figure 1). From Late Paleozoic to Mesozoic, the Western Liaoning region in the east of NCC has experienced a complex superimposition of the subduction and closure of the Paleo-Asian Ocean, the Paleo-Pacific tectonic regime, and the Mongolia-Okhotsk tectonic regime, which resulted in the thinning of the lithosphere and the strong tectonic-magmatic-metallogenic-basin-forming activities. The Mesozoic era is considered to be the main period of destruction of the NCC, which is the active period of strong Yanshan tectonic movement and magmatic activities such as lithospheric thinning and destruction, plate subduction, intracontinental orogeny, regional uplifting, and extension [18,22,41,53,54]. Therefore, Mesozoic volcanic rocks are closely related to such geological issues as the Mesozoic tectonic transformation in eastern China, crustal delamination and thinning in

eastern NCC, and the biota expansion, which directly affect geologists' understanding of the ages and background of different geological events. [6,41,55].

Volcanic rocks are well developed in Western Liaoning, mainly distributed in the Mesozoic Jinlingsi-Yangshan volcanic belt and Fuxin-Yixian basin belt [33,34,56]. The volcanic activities began in the Late Triassic and reached the peak in the Early Cretaceous. According to the residual strata of the present basin in the study area, the volcanic-sedimentary basins widely developed in Western Liaoning can be divided into Jurassic basin and Cretaceous basins, among which the Jurassic basin is the Jinlingsi-Yangshan basin, and the Cretaceous basin is more extensive, such as Xiaodeyingzi basin, Xintaimen basin, Sierbao-Baita basin, and so on (Figure 2a). The main strata developed are volcanic rocks of the Guajishan Formation and Yixian Formation which are distributed in a NE direction. With further research, it is gradually discovered that a large number of Jurassic volcanic-sedimentary strata develop in the original thought Cretaceous basin. The Xintaimen basin is located in the northwestern part of the Yangjiazhangzi magmatic-metallogenic belt (Figure 2a,b). The first $^{40}\text{Ar}/^{39}\text{Ar}$ dating results of the andesite and basaltic andesite exposed in the basin were from the late Early Cretaceous to the early Late Cretaceous (110.9–92.8 Ma) [46]. A large number of salamander fossils belonging to the Jehol biota were found in the lacustrine purple argillaceous siltstone interbedded with gray-green andesite [44,50], and the basin was classified as the Early Cretaceous basin. This study now reports that large-scale Early Jurassic volcanic rocks are distributed in the Xintaimen basin in the NNE direction, which rests angular discordant on the limestone of Early and Middle Proterozoic Wumishan Formation and the limestone strata of Early Paleozoic. The rock assemblages of the volcanic rocks are mainly intermediate-acidic volcanic rocks which are composed of trachyandesite, trachyte, trachydacite, and a small amount of rhyolite. The detailed determination of the analyzed volcanic rocks is of great significance for establishing the chronological framework, petrogenesis, and tectonic setting of Mesozoic volcanic rocks in the Western Liaoning region.

3. Sample Descriptions

The typical volcanic rocks were selected for systematic analysis, and the main samples were classified into two groups. Trachydacites with a light gray or light purple gray colors are the most widely distributed in the basin. They have a porphyritic texture, a massive structure, and a fluidal structure that can be seen locally. Phenocrysts account for 5–30% (Figure 3a,b), are mainly composed of plagioclase, hornblende, and biotite. The plagioclase is euhedral or subhedral granular with a polysynthetic twin. Some plagioclases have the characteristics of multiple crystallization, and the centers of some plagioclases have been altered. The hornblende is euhedral granular with black, some of which are directional. The matrix is a mikropoikilitic texture composed of irregular quartz inlaid with fine feldspar microcrystals (Figure 3c; YX-06).

Rhyolites are less exposed and mainly distributed in the trachyandesite interlayer. The weathered surface of the rocks is earth yellow, and the fresh surface is grayish-white or light yellow. It has a porphyritic and massive structure, and the phenocryst content is about 15–25%. The porphyritic minerals are mainly composed of plagioclase, hornblende, quartz, and a small amount of biotite. The plagioclase is euhedral granular with a slight alteration, and part of the plagioclase presents a polysynthetic twin. The hornblende is euhedral granular with dark green. Quartz is xenomorphic granular and biotite is a brown flake. The matrix is mainly a fluidal structure composed of quartz and feldspar and other microcrystalline minerals (Figure 3d; YX-07).

Figure 3. Representative meso- and micro-fabrics of Early Jurassic volcanic rocks. (a) Field outcrops of trachyticdacite. (b) Field outcrop of hornblende trachydacite (hornblende directional arrangement). (c) Trachyte amphibolite dacite (YX-06). (d) Rhyolite (YX-07). Note: Bi—Biotite; Hb—Hornblende; Pl—Plagioclase; Q—Quartz.

4. Analytical Methods

4.1. Zircon U–Pb Dating

The trachydacite (YX-06) and rhyolite (YX-07) were selected for zircon U–Pb isotopic dating. The sorting of zircon single mineral was completed in Langfang Regional Geological Survey, Hebei Province, China. The sample target was prepared and handmade in Beijing GeoAnaly/i/Co., Ltd., Beijing, China. LA–ICP–MS U–Pb zircon dating was carried out at the Key Laboratory of Mineral Resources Evaluation in Northeast Asia, Ministry of Natural Resources, Jilin University, Changchun, Jilin, China, using an ArF excimer laser system (GeoLas Pro, 193 nm wavelength) and a quadrupole ICP–MS (Agilent 7500a, Santa Clara, CA, USA). Some zircons have multiple zoning, however, we choose potential target sites carefully and ensured the reliability of our data which avoided a single analysis spot crossing multiple zones. Details of the analytical methods are given by Liang et al. [57]. The software Glitter was used to calculate the isotope ratio and element content. The data calculation and image rendering were processed using the ISOPLOT program (Version 3.23) [58]. Common Pb was corrected for following Andersen [59]. Uncertainties on individual analyses were reported with 1σ error and weighted mean ages were calculated at 1σ confidence level, representing the 95% confidence interval. The filtering of the U–Pb ages was based on a 10% cut-off of the calculated discordance ($\%U\text{--}Pb\text{ disc} = [1 - (^{206}Pb/^{238}U\text{ age}/^{207}Pb/^{235}U\text{ age})] \times 100$). The $^{206}Pb/^{207}Pb$ age for zircons with ages greater than 1000 Ma was used, instead, for grains younger than 1000 Ma, the $^{206}Pb/^{238}U$ age was used as the best age independence of the imprecise measurement of ^{207}Pb in young grains.

4.2. Major- and Trace-Element Analyses

The pre-processing and analysis of the whole-rock samples were completed in the Test Center of No.1 Bureau of China Metallurgical Geology Bureau, Hebei Province, China. The major elements were analyzed by an X-ray fluorescence spectrometer (XRF, Japan Rigaku), and the testing instrument was a sequential X-ray fluorescence spectrometer (AXIOS Minerals). Trace elements were tested by an inductively coupled plasma mass

spectrometer (ICP–MS Agilent 7500ce). Details of the analytical methods are given by Hu et al. [60].

4.3. Zircon Lu–Hf Isotope Analyses

Based on the LA–ICP–MS U–Pb zircon dating, the in situ zircon Hf isotopic analysis of Mesozoic volcanic rocks in the Xintaimeng basin was carried out. The analysis was conducted using a Neptune Plus MC–ICP–MS (Thermo Fisher Scientific, Darmstadt, Germany) in combination with a Geolas 2005 excimer ArF laser ablation system (193 nm) that was hosted at the Solid Isotope Laboratory of Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China. The analysis spots were 44 μm in diameter, and each measurement consisted of the 20 s of acquisition of the background signal followed by 50 s of acquisition of the ablation signal. The international standard sample 91,500 of zircon was used as the external standard for the measurement. The laser ablation rate was 8 Hz and the energy was 90 mJ. Offline processing of analysis data (including the selection of samples and blank signals, and isotope mass fractionation correction) was completed by ICPMSDataCal software. Details of the analytical techniques are given by Hu et al. [61].

5. Analytical Results

5.1. Zircon U–Pb Ages

Zircons from trachydacite YX-06 (N: $40^{\circ}55'25''$, E: $120^{\circ}24'46''$) and rhyolite YX-07 (N: $40^{\circ}56'11''$, E: $120^{\circ}26'50''$) are both euhedral-subhedral, with grain sizes ranging from 150–300 μm (Figure 4a,b). The elongation (length to width) ratios of zircons range from 1.5:1 to 2.5:1, suggesting a faster crystallization velocity. The CL image shows that the zircons have a clear internal structure, complete crystal shape, and mostly long columnar form, with a typical oscillatory growth zoning. Most zircons have locally preserved xenocrystic cores, which occur as cores mantled by newly grown zircon (Figure 4a,b). The occurrence of xenocrystic zircon is a common feature of many igneous rocks [62]. In addition, these zircons show continuity between core and rim, having high U contents (ranging from 101 to 6632 ppm) and Th/U ratios mostly between 0.26 and 3.19 (Table 1), indicating magmatic origin.

Figure 4. Cathodoluminescence images of representative zircons (a,b); Numbers on the images represent analysis spots, and the data near the images represent the associated ages) and $^{206}\text{Pb}/^{238}\text{U}$ vs. $^{207}\text{Pb}/^{235}\text{U}$ concordia plots of investigated samples (c,d). Errors are 1σ .

Table 1. LA-ICP-MS zircon U–Pb dating results for the volcanic rocks in the Xintaimen Basin, Western Liaoning.

Sample No.	Th (ppm)	U (ppm)	Th/U	Isotopic Ratio						Ages (Ma)						%U–Pb Disc
				²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	
YX-06-01	126	106	1.18	0.15030	0.00686	8.79709	0.36872	0.42451	0.00770	2349	80	2317	38	2281	35	1.6
YX-06-02	370	274	1.35	0.16626	0.00303	10.77461	0.23901	0.46608	0.00676	2520	19	2504	21	2466	30	1.5
YX-06-03	235	400	0.59	0.16640	0.00333	11.43097	0.23326	0.49483	0.00572	2522	19	2559	19	2592	25	−1.3
YX-06-04	441	447	0.99	0.05026	0.00306	0.21107	0.01256	0.03041	0.00061	207	100	194	11	193	4	0.5
YX-06-05	101	132	0.76	0.05685	0.00724	0.22788	0.03033	0.03013	0.00102	486	236	208	25	191	6	8.2
YX-06-06	105	404	0.26	0.15851	0.00273	9.98741	0.20354	0.45368	0.00702	2440	16	2434	19	2412	31	0.9
YX-06-07	1076	1339	0.80	0.16292	0.00287	11.11700	0.20958	0.49160	0.00752	2486	14	2533	18	2578	33	−1.8
YX-06-08	411	849	0.48	0.04891	0.00194	0.13912	0.00551	0.02054	0.00029	144	66	132	5	131	2	0.8
YX-06-09	7427	6632	1.12	0.04608	0.00114	0.19377	0.00532	0.03026	0.00052	2	28	180	5	192	3	−6.7
YX-06-10	296	281	1.05	0.05031	0.00274	0.19780	0.01078	0.02881	0.00050	209	94	183	9	183	3	0.0
YX-06-11	10,366	7825	1.32	0.04874	0.00086	0.18994	0.00392	0.02805	0.00040	135	24	177	3	178	3	−0.6
YX-06-12	1491	929	1.60	0.05165	0.00209	0.19276	0.00687	0.02729	0.00036	270	57	179	6	174	2	2.8
YX-06-13	2381	1128	2.11	0.04917	0.00292	0.14342	0.00848	0.02122	0.00042	156	98	136	8	135	3	0.7
YX-06-14	5136	1610	3.19	0.04964	0.00219	0.20056	0.00875	0.02922	0.00045	178	73	186	7	186	3	0.0
YX-06-15	1463	785	1.86	0.05113	0.00183	0.20564	0.00754	0.02902	0.00036	247	62	190	6	184	2	3.2
YX-06-16	107	128	0.84	0.05275	0.00729	0.19227	0.02146	0.02798	0.00087	318	195	179	18	178	5	0.6
YX-06-17	982	963	1.02	0.04967	0.00187	0.19740	0.00749	0.02875	0.00039	180	63	183	6	183	2	0.0
YX-06-18	3064	2820	1.09	0.04873	0.00132	0.19161	0.00518	0.02851	0.00038	135	39	178	4	181	2	−1.7
YX-06-19	257	285	0.90	0.05125	0.00323	0.19007	0.01227	0.02694	0.00052	252	113	177	10	171	3	3.4
YX-06-20	247	315	0.78	0.05619	0.00329	0.21788	0.01215	0.02859	0.00048	460	94	200	10	182	3	9.0
YX-06-21	8486	6180	1.37	0.04984	0.00084	0.20048	0.00357	0.02911	0.00032	188	22	186	3	185	2	0.5
YX-06-22	378	400	0.94	0.16506	0.00247	10.75859	0.18360	0.47098	0.00558	2508	14	2502	16	2488	24	0.6
YX-06-23	2039	2102	0.97	0.04966	0.00129	0.19437	0.00524	0.02836	0.00043	179	36	180	4	180	3	0.0
YX-06-24	2868	2806	1.02	0.04961	0.00408	0.14120	0.01132	0.02064	0.00038	177	187	134	10	132	2	1.5
YX-06-25	413	1200	0.34	0.16081	0.00248	9.48883	0.16754	0.42705	0.00506	2464	15	2386	16	2292	23	3.9
YX-07-01	987	808	1.22	0.05101	0.00191	0.13343	0.00530	0.01912	0.00040	241	54	127	5	122	3	3.9
YX-07-02	615	423	1.46	0.04605	0.00383	0.18094	0.01442	0.02850	0.00068		183	169	12	181	4	−7.1
YX-07-03	3100	2161	1.43	0.04878	0.00132	0.18999	0.00544	0.02889	0.00074	137	30	177	5	184	5	−4.0
YX-07-04	981	964	1.02	0.05016	0.00216	0.20700	0.00984	0.03013	0.00091	202	58	191	8	191	6	0.0
YX-07-05	370	506	0.73	0.16097	0.00280	8.64594	0.20583	0.39276	0.00917	2466	18	2301	22	2136	42	7.2
YX-07-06	3483	2379	1.46	0.05103	0.00222	0.12934	0.00555	0.01880	0.00065	242	45	124	5	120	4	3.2
YX-07-07	1416	1057	1.34	0.05126	0.00175	0.19380	0.00635	0.02787	0.00052	253	42	180	5	177	3	1.7
YX-07-08	636	661	0.96	0.05080	0.00212	0.21536	0.00879	0.03111	0.00053	232	63	198	7	198	3	0.0
YX-07-09	1257	1584	0.79	0.05304	0.00165	0.20652	0.00789	0.02810	0.00068	331	46	191	7	179	4	6.3
YX-07-10	1662	1807	0.92	0.04964	0.00131	0.19886	0.00595	0.02893	0.00048	178	40	184	5	184	3	0.0
YX-07-11	707	728	0.97	0.04990	0.00188	0.19117	0.00699	0.02788	0.00033	190	63	178	6	177	2	0.6
YX-07-12	417	491	0.85	0.05121	0.00283	0.19669	0.00963	0.02835	0.00042	250	85	182	8	180	3	1.1
YX-07-13	2471	2195	1.13	0.04972	0.00163	0.18538	0.00643	0.02693	0.00042	182	52	173	6	171	3	1.2
YX-07-14	609	404	1.51	0.05014	0.00309	0.18786	0.01133	0.02741	0.00053	201	103	175	10	174	3	0.6
YX-07-15	934	996	0.94	0.05017	0.00160	0.19444	0.00637	0.02809	0.00039	203	50	180	5	179	2	0.6
YX-07-16	600	721	0.83	0.05018	0.00184	0.19755	0.00734	0.02849	0.00035	204	63	183	6	181	2	1.1

Table 1. Cont.

Sample No.	Th (ppm)	U (ppm)	Th/U	Isotopic Ratio				Ages (Ma)								%U-Pb Disc
				$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	
YX-07-17	381	475	0.80	0.05468	0.00245	0.21181	0.00877	0.02842	0.00048	399	62	195	7	181	3	7.2
YX-07-18	614	784	0.78	0.05029	0.00171	0.19211	0.00627	0.02793	0.00036	209	51	178	5	178	2	0.0
YX-07-19	816	972	0.84	0.05158	0.00167	0.20313	0.00704	0.02858	0.00043	267	52	188	6	182	3	3.2
YX-07-20	489	484	1.01	0.05388	0.00341	0.19902	0.01200	0.02707	0.00058	366	97	184	10	172	4	6.5
YX-07-21	485	1216	0.40	0.15184	0.00225	7.16232	0.12706	0.34103	0.00409	2367	15	2132	16	1892	20	11.3
YX-07-22	495	601	0.82	0.04966	0.00213	0.19455	0.00907	0.02822	0.00047	179	77	181	8	179	3	1.1
YX-07-23	1120	1359	0.82	0.05007	0.00184	0.19815	0.00676	0.02887	0.00037	198	55	184	6	183	2	0.5
YX-07-24	408	476	0.86	0.04980	0.00300	0.18128	0.01101	0.02655	0.00051	186	104	169	9	169	3	0.0
YX-07-25	1529	1001	1.53	0.05842	0.00207	0.22493	0.00767	0.02805	0.00036	546	52	206	6	178	2	13.6

A total of 25 zircons were analyzed in trachydacite YX-06, all of which were located near the concordia curve (Figure 4c). The weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age from the 15 zircon grains is 181.9 ± 3.0 Ma (MSWD = 4.2, $n = 15$), which represents the timing of crystallization of this sample is late Early Jurassic. Seven zircon grains exhibit Paleoproterozoic ages, with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 2486 ± 31 Ma (MSWD = 3.8, $n = 7$), indicating inherited or captured zircons. The weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age from the two zircon grains is 132.1 ± 2.5 Ma (MSWD = 0.62, $n = 3$), which may be attributed to the later tectonic thermal events.

A total of 25 zircons tested from rhyolite YX-07 (Figure 4d) gave $^{206}\text{Pb}/^{238}\text{U}$ ages of 19 zircons which ranged from 169 to 191 Ma, with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 178.8 ± 1.9 Ma (MSWD = 2.2, $n = 19$), indicating the crystallization age of late Early Jurassic. The $^{206}\text{Pb}/^{238}\text{U}$ ages of the 2 zircons are 198 ± 3 Ma and 2466 ± 18 Ma, respectively, which may be the ages of the inherited zircons. The weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age from the two zircon grains is 121.3 ± 4.7 Ma (MSWD = 0.16, $n = 2$), indicating the late Early Cretaceous, which may represent the age of late tectonic thermal events. The two discordant ages probably are disturbed by Pb loss (%U–Pb disc > 10, Table 1), so they are inaccurate and are not used during our mapping.

5.2. Geochemical Features

5.2.1. Major Elements

Twelve typical fresh Early Jurassic intermediate-acidic volcanic rocks were selected for geochemical analysis, and the results are shown in Tables 2 and 3. The SiO_2 in volcanic rocks is 60.70–71.45 wt.%, which is a set of intermediate-acidic magmatic rocks. The volcanic rocks contain $\text{Mg}^\#$ [$\text{Mg}^\# = 100 \text{Mg}^{2+} / (\text{Mg}^{2+} + \text{TFe}^{2+})$] values of 16–48, 0.23–0.77 wt.% TiO_2 , 2.05–6.14 wt.% TFeO , 14.23–16.81 wt.% Al_2O_3 , 0.63–4.21 wt.% CaO , 3.46–6.01 wt.% Na_2O , 3.35–5.85 wt.% K_2O , 0.79–1.79 $\text{Na}_2\text{O}/\text{K}_2\text{O}$, and $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ concentrations of 7.79–11.28 wt.% (Table 2). In the total-alkali vs. silica (TAS) diagram (Figure 5a), they fall into trachyte and rhyolite areas respectively (the normative Quartz more than 20 wt.% in most samples). In the SiO_2 vs. K_2O diagram (Figure 5b), the samples mainly fall into the area of high-K calc-alkaline series, and a small amount falls into the area of the shoshonite series. They have A/CNK values of 0.99–1.09, indicating they are metaluminous to weakly peraluminous (Figure 5c).

Figure 5. Total-alkali ($\text{K}_2\text{O} + \text{Na}_2\text{O}$) vs. SiO_2 (TAS) diagram (a), after Irvine and Baragar [63]), SiO_2 vs. K_2O diagram (b), after Peccerillo and Taylor [64]) and $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$ (A/CNK) vs. $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})$ (ANK) diagram (c), after Maniar and Piccoli [65]) diagrams of the Early Jurassic volcanic rocks. F = Foidite; U1 = Tephrite/Basanite; U2 = Phonotephrite; U3 = Tephriphonolite; S1 = Trachybasalt; S2 = Basaltic trachyandesite; S3 = Trachyandesite; T = Trachyte/Trachydacite; Pc = Picrobasal; B = Basalt; O1 = Basaltic andesite; O2 = Andesite; O3 = Basite; R = Rhyolite.

Table 2. Major elements (wt.%) compositions for the Early Jurassic volcanic rocks.

Sample No.	Lithology	SiO ₂	TiO ₂	Al ₂ O ₃	TFeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI	Total	Mg [#]	Na ₂ O + K ₂ O	A/CNK	A/NK
N17-1	Trachydacite	68.59	0.37	15.48	2.69	0.03	0.51	0.76	5	4.96	0.15	1.46	100.29	25.3	9.96	1.03	1.14
N17-2	Trachydacite	69.67	0.36	15.51	2.49	0.04	0.27	2.07	4.28	4.53	0.16	0.82	100.45	16.1	8.81	0.99	1.30
N18-2	Trachydacite	67.28	0.38	16.24	2.71	0.04	0.49	1.41	5.07	4.5	0.16	1.7	100.27	24.2	9.57	1.03	1.23
N19-1	Trachydacite	67.44	0.37	16.06	2.6	0.04	0.41	1.54	5.22	4.27	0.16	1.86	100.24	21.8	9.49	1.00	1.22
N20-2	Trachydacite	69.05	0.34	15.59	2.54	0.03	0.3	1.19	6.01	3.35	0.16	1.38	100.22	17.2	9.36	0.99	1.15
N21-1	Trachydacite	66	0.52	15.39	4.51	0.07	1.78	2.11	3.95	3.82	0.3	2.42	101.37	41.3	7.77	1.06	1.45
N22-1	Trachydacite	67.05	0.36	15.34	2.88	0.05	0.55	1.84	4.35	4.43	0.17	2.96	100.29	25.5	8.78	1.00	1.28
N23-1	Rhyolite	71.45	0.28	14.23	2.69	0.03	0.57	1.17	3.97	5.02	0.11	1.02	100.84	27.4	8.99	1.01	1.19
YX-06	Trachydacite	65.47	0.41	15.29	3.38	0.08	1.66	2	3.46	4.34	0.19	3.9	100.54	46.7	7.8	1.09	1.47
YX-07	Rhyolite	71.39	0.28	14.41	2.44	0.06	0.4	0.63	4.35	5	0.1	1.26	100.58	22.5	9.35	1.05	1.15
YX-08	Trachydacite	68.9	0.24	15.16	2.43	0.2	0.65	1.61	4.15	4.73	0.09	2.12	100.56	32.4	8.88	1.02	1.27
S5234	Rhyolite	71.13	0.23	14.93	2.05	0.06	0.42	1.62	4.34	4.35	0.08	0.8	100.23	26.7	8.69	1.01	1.26

Table 3. Trace elements for the Early Jurassic volcanic rocks.

Sample No.	N17-1	N17-2	N18-2	N19-1	N20-2	N21-1	N22-1	N23-1	YX-06	YX-07	YX-08	S5234
Cr	9.05	6.95	5.66	5.84	6.47	10.9	13.2	6.76	26.5	11.5	6.90	8.49
Ni	2.03	2.58	2.21	2.39	3.90	9.34	6.31	3.91	15.4	4.34	2.23	2.82
Sc	1.92	2.54	2.34	2.23	2.63	4.42	3.00	2.72	4.17	2.61	3.01	2.34
Co	3.55	2.84	3.89	3.66	3.66	7.54	4.96	3.42	6.95	3.58	3.29	2.83
V	34.8	36.1	32.4	35.0	30.5	50.3	36.1	28.9	45.9	23.3	20.8	24.8
Ba	1459	1529	1565	1402	926	1451	1330	1299	1493	907	915	947
Rb	119	113	115	109	76.4	95.8	119	150	113	133	93.4	88.4
Th	3.29	4.57	4.44	4.03	3.92	4.80	4.00	10.5	4.59	7.83	3.23	2.92
U	0.89	1.45	1.10	1.11	1.09	1.37	1.19	1.77	1.12	1.70	0.58	0.81
Nb	12.5	11.9	12.2	12.5	15.3	14.0	13.3	10.4	12.6	10.4	9.75	9.05
Ta	0.93	1.01	1.01	1.00	1.13	1.08	1.10	1.06	0.97	0.83	0.62	0.76
Sr	541	748	800	865	458	632	695	453	565	156	340	395
Zr	157	152	157	155	150	153	153	165	152	165	120	113
Hf	8.02	7.26	7.05	6.54	6.90	6.74	6.30	5.50	6.14	4.75	6.42	4.17
Y	5.7	6.0	6.8	7.2	7.5	7.2	7.3	6.4	7.4	6.0	6.81	5.95
Pb	15.6	17.8	18.8	17.8	18.7	19.7	17.5	24.6	18.1	19.7	17.0	18.0
Ga	15.2	17.8	18.4	17.5	18.6	18.8	15.6	16.3	18.6	13.3	16.3	16.2
Cs	1.08	1.71	1.44	1.22	0.96	1.14	1.36	1.95	2.72	0.90	0.47	0.67
La	13.62	25.31	31.46	31.37	31.00	33.33	18.19	32.12	24.15	29.54	20.20	17.58
Ce	36.67	54.05	59.75	64.10	61.85	66.30	47.18	68.40	56.42	61.98	43.21	40.87
Pr	4.95	6.17	7.10	7.17	6.85	8.11	6.11	7.46	6.64	6.37	5.43	4.85
Nd	17.87	20.38	23.03	23.29	22.11	26.94	21.51	22.69	22.46	19.42	17.90	16.30
Sm	2.92	3.25	3.32	3.40	3.44	4.15	3.64	3.52	3.67	2.91	2.67	2.52
Eu	0.84	0.95	1.04	1.05	0.93	1.29	1.01	0.83	1.12	0.65	0.81	0.67
Gd	2.47	2.77	3.01	3.01	2.98	3.52	2.90	2.61	2.88	2.52	2.46	2.29
Tb	0.29	0.30	0.32	0.35	0.35	0.38	0.34	0.32	0.34	0.27	0.29	0.26
Dy	1.31	1.33	1.46	1.53	1.61	1.69	1.63	1.40	1.62	1.23	1.37	1.20
Ho	0.22	0.22	0.26	0.25	0.27	0.28	0.27	0.25	0.28	0.23	0.25	0.20
Er	0.58	0.64	0.68	0.77	0.79	0.79	0.78	0.67	0.81	0.64	0.69	0.64
Tm	0.09	0.10	0.10	0.10	0.12	0.11	0.11	0.11	0.11	0.09	0.11	0.10
Yb	0.55	0.65	0.65	0.70	0.75	0.70	0.73	0.66	0.71	0.60	0.72	0.62
Lu	0.09	0.10	0.09	0.11	0.11	0.10	0.11	0.10	0.10	0.09	0.11	0.10
Eu*	0.93	0.95	0.99	0.99	0.87	1.01	0.92	0.80	1.02	0.71	0.95	0.84
Sr/Y	94.28	123.59	117.94	120.28	60.82	87.49	94.91	70.81	76.24	25.80	49.86	66.48
ΣREE	82	116	132	137	133	148	105	141	121	127	96	88
(La/Yb) _N	16.70	26.40	32.55	30.37	27.97	32.27	16.74	32.79	22.89	33.10	18.98	19.25
Nb/Ta	13.52	11.77	12.05	12.55	13.56	12.96	12.15	9.78	13.04	12.55	15.71	11.93
(Gd/Yb) _N	3.63	3.46	3.73	3.49	3.21	4.08	3.19	3.19	3.27	3.38	2.77	3.00
Ce/Pb	2.35	3.04	3.19	3.60	3.31	3.37	2.69	2.78	3.12	3.15	2.54	2.27
Nb/U	14.16	8.25	11.11	11.28	14.03	10.22	11.26	5.85	11.29	6.10	16.73	11.22

According to the Harker diagram (Figure 6), there is a negative correlation between the major elements and SiO₂. These geochemical variations can be attributed to mineral fractional crystallization during magmatic evolution. MgO, TFeO, CaO have an approximately negative correlation with SiO₂, which may indicate the fractional crystallization of clinopyroxene and hornblende. The decreases in Al₂O₃ and Sr concentrations with increasing SiO₂ probably relate to the fractionation of plagioclase. In addition, the decrease in TiO₂

with increasing SiO_2 content can be attributed to fractional crystallization of titaniferous minerals such as rutile, ilmenite, and sphene. In summary, we propose that mineral fractional crystallization during magmatic evolution is responsible for compositional variations in these volcanic rocks.

Figure 6. Variations of major elements vs. SiO_2 diagrams (Harker diagrams) of the Early Jurassic volcanic rocks.

5.2.2. Trace and Rare Earth Elements

In the primitive mantle normalized trace element spidergrams (Figure 7a), the samples are relatively enriched in large ion lithophile elements (LILEs; e.g., Ba, Rb, K, and Sr), depleted in high field strength elements (HFSEs; e.g., Nb, Ta, Ti, and P), and have obvious geochemical characteristics of positive Pb anomalies. The samples are enriched in LILEs, Pb, and HFSEs (Zr and Hf), in which Ba is more enriched than Rb and Th, and HFSEs (Nb, Ta, and Ti) are relatively depleted, indicating the characteristics of continental crust. The ratios of Sr/Y and Nb/Ta are high, and the contents of LILEs such as Sr (340–865 $\mu\text{g/g}$, except XY-07), Ba (907–1565 $\mu\text{g/g}$), U (0.58–1.77 $\mu\text{g/g}$), and Th (2.92–10.5 $\mu\text{g/g}$) are high, which are similar to the geochemical characteristics of adakitic volcanic rocks. In the chondrite normalized REE patterns (Figure 7b), the samples are enriched in light rare earth elements (LREEs) and depleted in heavy rare earth elements (HREEs), showing an overall right-leaning curve as a whole, with obvious fractionation of light and heavy rare earth elements ($(\text{La/Yb})_N = 16.70\text{--}38.71$), as well as weak negative Eu anomalies ($\delta\text{Eu} = 0.7\text{--}1.04$). The Yb content is less than 0.75 $\mu\text{g/g}$, and the Y content

is less than 7.5 $\mu\text{g/g}$, which may imply that there are residual garnet and other minerals in the source area and the crystallization separation of the plagioclase is not obvious during the original magma evolution. The lower contents of the compatible elements Co (2.83–7.54 $\mu\text{g/g}$), Ni (2.03–15.4 $\mu\text{g/g}$), and Cr (5.66–26.5 $\mu\text{g/g}$) suggest that the magma may have originated from partial melting of crustal materials.

Figure 7. Primitive mantle normalized trace element spidergrams (a), after Sun and McDonough [66] and chondrite normalized rare earth element (REE) patterns (b), after Boynton [67] of the Early Jurassic volcanic rocks.

5.3. Zircon Hf Isotopes

On the basis of U–Pb zircon dating, Lu–Hf isotopic analysis of representative zircons was carried out, and the analysis results are shown in Table 4. The results show that the $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of the seven zircons with a crystallization age of about 181 Ma in the sample YX-06 range from 0.282222 to 0.282339. The corresponding $\varepsilon_{\text{Hf}}(t)$ values range from -16.0 to -11.7 , and the two-stage model ages ($T_{\text{DM}2}$) range from 1961 to 2232 Ma, suggesting that the source area may be derived from the ancient lower crust of the Proterozoic (Table 4, Figure 8). It is worth noting that the ~ 174 Ma zircon have $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.282619, $\varepsilon_{\text{Hf}}(t)$ value of -2.3 , and the two-stage model age ($T_{\text{DM}2}$) of 1363 Ma, indicating that the magma source area may be contributed by depleted mantle material (Table 4, Figure 8). The $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of the 13 zircons with a crystallization age of about 178 Ma in the sample YX-07 range from 0.282337 to 0.282457. The corresponding $\varepsilon_{\text{Hf}}(t)$ values range from -11.6 to -7.4 , and the two-stage model ages ($T_{\text{DM}2}$) range from 1692 to 1958 Ma, which also suggests that the magma may be derived from the Proterozoic lower crust (Figure 8).

Figure 8. Zircon Hf isotopic characteristics of Early Jurassic volcanic rocks in the geological corridor of western Liaoning (a), after Yang et al. [68]; (b), after Wu et al. [69]). CAOB = Central Asian Orogenic Belt; NCC = North China Craton.

Table 4. Zircon Hf isotopic data for the Early Jurassic volcanic rocks.

Sample No.	t (Ma)	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	2σ	$\epsilon_{\text{Hf}}(0)$	$\epsilon_{\text{Hf}}(t)$	2σ	T_{DM1}	T_{DM2}	$f_{\text{Lu/Hf}}$
YX-06 01	181	0.017562	0.000732	0.282267	0.000024	−17.9	−14.0	0.9	1381	2109	−0.98
YX-06 02	174	0.159603	0.006290	0.282619	0.000029	−5.4	−2.3	1.0	1042	1363	−0.81
YX-06 03	181	0.072934	0.002811	0.282339	0.000026	−15.3	−11.7	0.9	1353	1961	−0.92
YX-06 04	181	0.036005	0.001416	0.282314	0.000022	−16.2	−12.4	0.8	1339	2008	−0.96
YX-06 05	181	0.024457	0.000980	0.282333	0.000016	−15.5	−11.7	0.6	1297	1963	−0.97
YX-06 06	181	0.013396	0.000554	0.282286	0.000020	−17.2	−13.3	0.7	1347	2063	−0.98
YX-06 07	181	0.101319	0.004242	0.282222	0.000021	−19.4	−16.0	0.7	1588	2232	−0.87
YX-06 08	181	0.040907	0.001688	0.282278	0.000016	−17.5	−13.7	0.6	1399	2090	−0.95
YX-07 01	178	0.026983	0.001225	0.282337	0.000021	−15.4	−11.6	0.7	1300	1958	−0.96
YX-07 02	178	0.018633	0.000788	0.282376	0.000020	−14.0	−10.2	0.7	1231	1868	−0.98
YX-07 03	178	0.025697	0.001121	0.282368	0.000019	−14.3	−10.5	0.7	1252	1887	−0.97
YX-07 04	178	0.021462	0.001011	0.282384	0.000020	−13.7	−9.9	0.7	1227	1851	−0.97
YX-07 05	178	0.031338	0.001402	0.282397	0.000018	−13.3	−9.5	0.6	1221	1824	−0.96
YX-07 06	178	0.041823	0.001694	0.282457	0.000025	−11.1	−7.4	0.9	1145	1692	−0.95
YX-07 07	178	0.039303	0.001810	0.282378	0.000020	−13.9	−10.2	0.7	1261	1869	−0.95
YX-07 08	178	0.017971	0.000770	0.282425	0.000016	−12.3	−8.5	0.6	1162	1758	−0.98
YX-07 09	178	0.022984	0.001002	0.282416	0.000019	−12.6	−8.8	0.7	1181	1779	−0.97
YX-07 10	178	0.032837	0.001463	0.282341	0.000021	−15.2	−11.5	0.8	1301	1949	−0.96
YX-07 11	178	0.027010	0.001296	0.282408	0.000017	−12.9	−9.1	0.6	1202	1799	−0.96
YX-07 12	178	0.027195	0.001181	0.282402	0.000018	−13.1	−9.3	0.6	1206	1811	−0.96
YX-07 14	178	0.028510	0.001198	0.282403	0.000021	−13.0	−9.3	0.7	1206	1809	−0.96

6. Discussion

6.1. Formation Ages

The Xintaimen basin in Western Liaoning was well-known in recent years because of a large number of the Jehol biota fossils in the lacustrine sediments, such as the *Liaoxitriton zhongjiani* and associated *Eosestheria* and *Liaoningocladusboii* [44,45]. It consists of the Lower Cretaceous Yixian Formation and/or Jiufotang Formation. Further research from Sun et al. conducted $^{40}\text{Ar}/^{39}\text{Ar}$ dating of widely developed volcanic rocks, which indicated their likely formation in the late Early Cretaceous or the early Late Cretaceous (93–110 Ma) [46]. However, the latest zircon U–Pb dating results of volcanic rocks in this paper show that the Xintaimen basin also developed a large range of Early Jurassic acidic volcanic rocks, with a formation age of 178.6–181.9 Ma. The rock assemblages are trachyandesite, trachydacite, a small amount of rhyolite and andesitic pyroclastic rocks, which are spatially distributed in the NNE or NS direction.

The Eastern Hebei and Western Liaoning areas on the eastern margin of the NCC were successively affected by the interaction of the Tethyan tectonic domain, the Paleo-Asian Ocean tectonic domain, and the Paleo-Pacific tectonic domain. Massive igneous rocks have been exposed in the Yanshan region located on the northern margin which is characterized by the superposition of multi-stage tectonic-magmatic activities [6,39,43,55,70,71]. The activity of Mesozoic vulcanism can be divided into four periods: Early Jurassic (Nandaling or Xinglonggou Period), Late Jurassic (Tiaojishan or Lanqi Period), Early Cretaceous (Zhangjiakou or Yixian Period), and Late Cretaceous (Daxingzhuang Period) [6,29,35–37,39,43,71,72]. Among these, the distribution range of Early Jurassic volcanic rocks is relatively limited and weak inactivity. The volcanic rocks are mainly composed of basalt, basaltic trachyandesite, andesite, trachyandesite, trachyte, and dacite [6,35–37,43]. The sporadic intermediate-basic volcanic rocks (174 Ma) from the Nandaling Formation in Xishan, Beijing, the intermediate volcanic rocks (202–177 Ma) from the Xinglonggou Formation in Beipiao, Western Liaoning, and the intermediate volcanic rocks (183–173 Ma) from the Haifanggou Formation in Beipiao, Western Liaoning are all products of volcanic activities in this period [43,55,70,71], which is basically consistent with the dating results of this paper (178.6–181.9 Ma).

6.2. Petrogenesis and Magma Source

The Early Jurassic volcanic rocks in the Western Liaoning are a set of intermediate-acidic rock assemblages, including trachyandesite, trachydacite, and a small amount of rhyolite and basaltic trachyandesite. From the perspective of petrochemical characteristics,

Early Jurassic volcanic rocks have adakitic geochemical characteristics, such as high SiO_2 (60.94–71.45 wt.%), Al_2O_3 (≥ 14.41 wt.%), and Na_2O (≥ 3.46 wt.%), with high Sr content between 395–1022 ppm (except YX-07, YX-08), low Y (5.74–15.68 ppm, < 18 ppm), and Yb (0.55–1.58 ppm, < 1.9 ppm). The samples are enriched in LREEs and LILEs, depleted in HREEs and HFSEs [2,73], without Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.71\text{--}1.07$), and fall into the adakitic rocks area in $(\text{Yb})_{\text{N}}\text{--}(\text{La}/\text{Yb})_{\text{N}}$ and Y–Sr/Y diagrams (Figure 9a,b). Therefore, this set of Early Jurassic intermediate-acidic volcanic rocks should be adakitic rocks.

Figure 9. Discriminant diagram of adakite rocks and SiO_2 concordant diagram. (a) $(\text{La}/\text{Yb})_{\text{N}}\text{--Yb}_{\text{N}}$ diagram; (b) Sr/Y–Y diagram; (c) Cr vs. SiO_2 diagram; (d) V vs. SiO_2 diagram; (e) $\text{CaO}/\text{Al}_2\text{O}_3$ vs. SiO_2 diagram. (f) Dy/Yb vs. SiO_2 diagram.

The rocks can be produced by the partial melting of the subducting oceanic crust interacting with the overlying mantle peridotite [2,73], by the crystallization differentiation of basaltic magma and crustal contamination [3], by partial melting of basaltic rocks and eclogite in the delamination lower crust [6,74,75], or by partial melting of ancient (thickened) basaltic lower crust [35,36,76,77]. However, the high K_2O content, $\text{K}_2\text{O}/\text{Na}_2\text{O}$ and Sr/Y ratios, low HREEs, weak negative Eu anomaly, and inherited zircon with crystalline basement age indicate that the volcanic rocks cannot have been formed in the partial melting of subducted oceanic plate [37,71]. At the same time, the SiO_2 content of most samples is higher ($> 66\%$), with low MgO , $\text{Mg}^\#$, Cr, Ni, and other characteristics, which are also different from the partial melting characteristics of the hydrated mantle [2,73].

Lower MgO, Cr, Ni, Sc, Co contents and $Mg^\#$ values [75,78], combined with the fact that Early Jurassic basalts have not been found in the Xintaimen area, indicate that the initial magma was not the product of crystallization differentiation of basaltic magma, or was not affected by mantle magma contamination, or did not interact with mantle peridotite, which excludes it as the product of partial melting of the delamination lower crust (Figure 10d). Low Ce/Pb (<3.6), Th, and U values indicate that lower crust materials are involved in the source area or magma evolution [79], and their higher Sr/Y ratios may be the characteristics of the inherited source area. In addition, the linear relationship between the major elements and SiO_2 content suggests the existence of fractional crystallization during the magmatic evolution [80]. Furthermore, the Lu-Hf isotope results show that the value of $\epsilon_{Hf}(t)$ ranges from -11.6 to -7.4 , and the two-stage model ages (T_{DM2}) range from 1692 to 1958 Ma, indicating that its magma source should be the partial melting of the lower crust of the Proterozoic (Figure 8). Therefore, this set of intermediate-acidic adakitic volcanic rocks originated from partial melting of the Proterozoic basaltic rocks in the lower crust of the NCC, nevertheless mantle-derived magma may also be involved. The partial melting of the lower crust caused by the underplating of basaltic magma is considered to be one of the main mechanisms for the formation of Mesozoic adakitic rocks in North China [5,35,36,76,77]. In the inland areas far from the subduction zone, the underplating event of mantle-derived basaltic magma cannot only thicken the lower crust, but also provide huge heat energy to promote partial melting of the lower crust rock to form adakitic magma [5,81]. Early-Middle Jurassic zircon ages in the lower crustal xenoliths of the Hannuo Dam in North China, indicate that there was a magmatic underplating event during the Early Jurassic–Middle Jurassic [25,55,82]. The underplating basaltic magma is generally considered to be not involved in the melting process or to play a lower role, resulting in the formation of adakitic magma with low Cr, Ni, Co, SC, $Mg^\#$, and MgO contents, which is similar to the geochemical characteristics of Early Jurassic intermediate-acidic volcanic rocks in the study area. The underplating basaltic magma may also have crust-mantle interaction with the lower crustal magma, forming a small amount of basaltic magma, and leading to the abnormal value of $\epsilon_{Hf}(t)$ [52]. Therefore, during the process of basaltic magma in the NCC underplating the basic lower crust in the Early Jurassic, the mantle-derived magma underwent fractional crystallization while heating the overlying ancient (Proterozoic) lower crust, and part of the thickened crust melted to form adakitic magma. Because the Ni, Cr concentrations and $Mg^\#$ values have not increased significantly, adakitic magma may not be mixed with differentiated mantle-derived magma, or only mixed with a small amount of differentiated mantle-derived magma. Then, the acidic magma chamber was formed by fractional crystallization of mafic minerals, and finally, it rose rapidly and was expelled from the surface to form intermediate-acidic volcanic rocks with high Sr/Y and low REE.

Figure 10. Tectonic discrimination diagrams (a–c) and SiO₂–MgO diagram (d), after Lai and Qi [83] for the Early Jurassic volcanic rocks.

6.3. Geological Implication

Western Liaoning is located in the superposition of the Tethys tectonic domain, the Paleo-Asian Ocean tectonic domain and the Paleo-Pacific tectonic domain [84]. It is one of the important regions for studying intracontinental orogeny, Yanshan movement, lithospheric thinning, and destruction of NCC [6,18,30,85,86]. The Yanshan region experienced large-scale tectonic deformation and magmatic activities, and developed a large-scale NE–NNE-trending fault basin. During the Mesozoic, it experienced the transition from convergence regime dominated by the Paleo-Asian Ocean tectonic domain to the subduction regime dominated by the Paleo-Pacific tectonic domain [29,51,72,77,87–89], which led to strong tectonism, magmatism, and mineralization [40,41,90].

The Early Jurassic volcanic rocks are sporadically distributed in Eastern Hebei and Western Liaoning, including the Nandaling Formation in Xishan, Beijing, Xinglonggou Formation in Chengde, Hebei and Western Liaoning, and Haifanggou Formation in Western Liaoning [6,35–37,39,43,71]. Discussions on their tectonic backgrounds continue to this day. For example, the products of the Mongolia–Okhotsk Ocean closure and the Farallon Plate double-subduction [42], the intraplate environment, which is related to the subduction of the Paleo-Pacific plate [43], and the long-range effect of the Mongolia–Okhotsk Ocean closure [91] and so on. In general, the Early Jurassic volcanic rocks all have the characteristics of adakitic rocks, and their genesis is closely related to the basaltic magma underplating event [6,36,37,39,42,43,91].

The Early Jurassic volcanic rocks are mainly a set of intermediate-acidic rock assemblages, including trachyandesite, trachydacite, and a small amount of rhyolite, which are similar to the rock assemblages in the active continental margin environment [92,93]. The major elements indicate that most of the Early Jurassic volcanic rocks belong to the high-K calc-alkaline series of rocks, and a small number of them belong to the alkaline series. The calc-alkaline rock assemblage is considered to be an effective indicator of paleosubduction [38]. The trace elements show that the volcanic rocks are enriched in LREEs and LILEs (such as Ba, Rb, K, Pb), and depleted in HREEs and HFSEs (such as Nb, Ta, P, Ti, Y) (Figure 7), indicating the geochemical characteristics of the igneous rocks in the active continental margin [80,94,95]. In addition, the contemporaneous Early–Middle Jurassic

granitic rock assemblages in the Western Liaoning are monzogranite and syenogranite. The major elements indicate by the high-K calc-alkaline series are metaluminous-weakly peraluminous, and is a I type granite. The trace elements are enriched in LREEs and LILEs, depleted in HREEs and HFSEs [96], similar to the geochemical characteristics of volcanic rocks, indicating the geochemical characteristics of igneous rocks in active continental margin similar to volcanic rocks. The common presented strong Nb and Ta depletion (Figure 7) implies in a volcanic island arc tectonic environment associated with subduction. In the tectonic environment discriminant diagram (Figure 10a–c), the samples also show the geodynamic setting of the subducted volcanic island arc, which belongs to the adakitic rock formed by partial melting of the thickened lower crust (Figure 10d), and the active continental margin environment [80,97]. This may be related to the long-range effect of the Paleo-Pacific plate subduction, but the influence of the Mongolia-Okhotsk Ocean closure is not excluded.

Before the Early Jurassic, a large number of fold structures with nearly EW trending and thrust nappes structures with hanging wall pointing to the south were developed in the Eastern Hebei and Western Liaoning. The whole region was under a compressive stress field of nearly SN trend, which may be related to the compressive deformation in the SN direction caused by the subduction of the Paleo-Asian Ocean in the region [51,98,99]. Subsequently, the Early Jurassic entered the joint influence period of the Paleo-Pacific tectonic domain and Mongolian-Okhotsk tectonic domain [38,100–102], and the transformation occurred from post-orogenic extension to intracontinental compression orogeny. The regional lower crust thickened under the dual-long-range effect of the Mongolia-Okhotsk Ocean closure and the Paleo-Pacific plate subduction [43,103]. In this thickened lower crust environment, the enriched lithospheric mantle partially melted, and the basaltic magma underplated into the ancient lower crust, resulting in the partial melting to form intermediate-acidic adakitic volcanic rocks (Figure 11).

Figure 11. Tectonic evolution of the northern North China Craton during Early Jurassic (modified after Ma, 2013 [71]). MOO = Mongolia-Okhotsk Ocean; NCC = North China Craton; PPO = Paleo-Pacific Ocean; SC = Siberian Craton; XMOB = Xing'an Mongolian Orogenic Belt; SLB = Solonker-Linxi Suture Belt; YS = Yanshan orogen; TLF = Tan-Lu Fault.

7. Conclusions

Based on the study of petrography, zircon U–Pb geochronology, geochemistry, and zircon Hf isotope of Early Jurassic volcanic rocks in the Western Liaoning, the following main conclusions were drawn:

(1) The latest zircon U–Pb geochronology results show that in addition to the Early Cretaceous volcanic rocks, a wide range of Early Jurassic intermediate-acidic volcanic rocks also developed in the Xintaimen basin. The formation age is 178.6–181.9 Ma, and the rocks are spatially distributed in the NE direction.

(2) The Early Jurassic volcanic rocks are mainly composed of trachyandesite and a small amount of rhyolite. The geochemical characteristics show high contents of SiO₂, Al₂O₃, and Na₂O, high contents of Sr and low contents of Y and Yb, enrichment in LREEs and LILEs, and depletion in HREEs and HFSEs, without Eu anomalies, indicating that they are a set of intermediate-acidic adakitic volcanic rock in high-K calc-alkaline series.

(3) The Early Jurassic Western Liaoning was under the long-range tectonic effects of the closure of the Mongolia-Okhotsk Ocean and the subduction of the Paleo-Pacific plate,

which caused the basaltic magma to invade the lower crust of the North China Craton. The mantle-derived magma was separated and crystallized while heating the Proterozoic lower crust, part of the thickened crust melted to form intermediate-acidic adakitic volcanic rocks.

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