Article

Petrogenesis of the Early Cretaceous Hongshan Complex in the Southern Taihang Mountains: Constraints from Element Geochemistry, Zircon U-Pb Geochronology and Hf Isotopes

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Abstract: The Hongshan complex, located in the southern part of the Taihang Mountains in the central part of the North China Craton, consists of syenite stocks (including fine-grained biotite aegirine syenite, medium-grained aegirine gabbro syenite, coarse-grained aegirine gabbro syenite, syenite pegmatite, and biotite syenite porphyry), with monzo-diorite and monzo-gabbro dikes. This paper presents zircon U-Pb ages and Hf isotope data and whole-rock geochemical data from the Hongshan complex. LA-ICP-MS zircon U-Pb age from the fine-grained biotite aegirine syenite, monzo-diorite, and monzo-gabbro are 129.3 ± 2.0 Ma, 124.8 ± 1.3 Ma, and 124.1 ± 0.9 Ma, respectively, indicating their emplacement in the Early Cretaceous when the North China Craton was extensively reactivated. The monzo-diorite and monzo-gabbro have low SiO_2 contents (48.94–57.75 wt%), total alkali contents (5.2–9.4 wt%), and $\epsilon_{\text{Hf}}(t)$ values of -22.3 to -18.4 and are enriched in MgO (4.0–8.2 wt%), Al_2O_3 (14.3–15.8 wt%), light rare earth elements (LREEs) and large ion lithophile elements (LILEs). Interpretation of elemental and isotopic data suggests that the magma of monzo-diorite and monzo-gabbro were derived from partial melting of the enriched lithospheric mantle metasomatized by slab-derived hydrous fluids. Syenites with high alkali ($\text{K}_2\text{O} + \text{Na}_2\text{O} = 9.4\text{--}13.0$ wt%) and Sr contents (356–1737 ppm) and low Yb contents (0.94–2.65 ppm) are enriched in Al ($\text{Al}_2\text{O}_3 = 16.4\text{--}19.1$ wt%), but depleted in MgO (0.09–2.56 wt%), Cr (Avg = 7.16 ppm), Co (Avg = 6.85 ppm) and Ni (Avg = 9.79 ppm), showing the geochemical features of adakitic rocks associated with thickened lower crust. Combining zircon $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.282176 to 0.282359, $\epsilon_{\text{Hf}}(t)$ values of -18.3 to -11.8 and $\epsilon_{\text{Nd}}(t)$ values of -11.1 to -8.2 , we conclude that the syenite magma was derived from the mixing of the thickened lower crust and the enriched lithospheric mantle magma. These magma processes were controlled by Paleo-Pacific plate subduction and resulted in the destruction and thinning of the central North China Craton.

Keywords: Hongshan complex; syenite; diorite-gabbro; crust–mantle interaction; Southern Taihang Mountains; North China Craton

1. Introduction

The North China Craton (NCC), one of the oldest landmasses on Earth [1], experienced stable development from the formation of the basement at ~1.8 Ga to the Triassic. In the

Early Jurassic, the NCC was reactivated and was disturbed as the lithosphere thinned due to the subduction of the Paleo-Pacific plate. The thickness of the NCC decreased from approximately 200 km in the Paleozoic to 80–120 km in the Cenozoic [2–4]. The margins and interior of the NCC are associated with Mesozoic large-scale mantle-crust magma activities, accompanied by the uplift and extension of the continental crust [5–7]. With the recent implementation of many research programs focusing on the NCC, it has been recognized by many geologists that the NCC was destroyed on a large scale in the Mesozoic [8]. However, there are different views on the dominant mechanism and dynamic background of NCC lithospheric thinning [2,3,8–12].

The Handan area is located in the southern part of the Taihang Mountains in the central part of the NCC, which is also the westernmost boundary of NCC destruction [3]. The Mesozoic regional magmatic activity is strong [13,14], which is a good place to study the lithospheric thinning mechanism in the central NCC. Traditionally, the alkaline rocks, typical rocks in the lithospheric extensional environment, are the products of the lower crust-mantle interaction during collisional orogenesis and lower crust thinning and are a shallow crust-level manifestation of and a natural "window" to magnify deep geodynamic processes [15–21]. Therefore, this paper selects the early Cretaceous Hongshan alkaline complex exposed in the southern end of the Taihang Mountains tectonomagmatic belt as the focus of this study [22,23] (Figure 1a). Based on previous studies, we systematically carry out field investigations, the petrology, elemental geochemistry, zircon U-Pb geochronology, and zircon Hf isotopic analysis of the Hongshan complex aimed at constraining the petrogenesis and related crust-mantle process during the craton destruction.

2. Geological Setting and Petrology of the Hongshan Complex

2.1. Geological Setting

The NCC is one of the major Archean cratons in eastern Eurasia [24,25] and has experienced geodynamic evolution for at least 3.8 billion years [26]. Based on lithological, geochemical, geochronological, structural, and metamorphic P–T path studies of the basement rocks, it can be divided into Eastern and Western Blocks, separated by Central Orogenic Belt (Figure 1a) [27–31]. The study area is located in the southern part of the Taihang Mountains in the Central Orogenic Belt, sharing boundaries with the crust-level faults of Shanqian and Xibaiyu [32,33]. The regional Archean basement is mainly composed of tonalite-trondhjemite-granodiorite (TTG) gneiss and supracrustal rocks of the Archean Zhanhuang group [34], which is unconformity covered by the young sediments, including the sandstone of Changzhongou Formation in Mesoproterozoic, Cambrian to Ordovician (Paleozoic) marine carbonate rocks, Carboniferous to Permian (Paleozoic) sandstone and Mesozoic volcanic rocks (Figure 1b). The volcanic event of the late Mesozoic formed a large outcrop of intermediate-felsic stocks. It can be divided into three magmatic zones from west to east in this region (including the Shexian complex, the Wu'an complex, and the Hongshan complex) [34] (Figure 1b). The Shexian complex (including Pingshun, Dongye, and Fushan) is distributed in the west and consists of gabbro and diorite. The rocks of the Wu'an complex in the central part (including Qicun, Kuangcun, and Guzhen) are dioritic and monzonitic in composition. The dominant rocks of the Hongshan complex in the east part are syenites [23,35,36]. These rocks were all emplaced in Paleozoic carbonate and sandstone strata.

Figure 1. (a) Simplified geological map showing the major tectonic units of the North China Craton(modified after [1]); (b) Geological map showing the distribution of the intrusive complexes in Handan district (modified after [36,37]).

2.2. Geology and Petrology of the Hongshan Complex

The Hongshan complex is located in the easternmost part of the magmatic belt in the southern Taihang Mountains, with an exposed area of about 50km² (Figures 1b and 2). Shen et al. (1977) divided regional intrusive rocks into gabbro diorite-hornblende diorite series, diorite-monzonite series, and alkaline syenite series, which are considered to be the products of homologous magma evolution. After that, many geologists have done much scientific research on the Hongshan complex [23,24,36–39]. Recently, based on field geological mapping and borehole logging of Hongshan complex, we have identified syenite, monzo-diorite (MD), and monzo-gabbro (GD) and divided the syenite into fine-grained biotite aegirine syenite (FBAS), medium-grained aegirine gabbro syenite (MAS), coarse-grained aegirine gabbro syenite (CAS), syenite pegmatite (SP) and biotite syenite porphyry (BSP). The geological and petrographic characteristics of each lithofacies are as follows:

Figure 2. Geological map of the Hongshan complex and the locations of the samples(modified after No. 1 Geological Team of Hebei Bureau of Geological Exploration and Development).

2.2.1. Syenite Facies

(1) Fine-grained biotite aegirine syenite (FBAS)

This lithofacies occurs as an irregular intrusion with an exposed area of approximately 8 km² (Figures 2 and 3a). The rocks are massive and fine-grained (Figure 4a), and the mineral assemblage with sizes of 0.3–0.8 mm consists of orthoclase (60–65%), aegirine pyroxene (13–15%), biotite (10–15%), plagioclase (8–12%), with the accessory minerals of magnetite, apatite, and zircon. The majority of orthoclase crystals are either subhedral or granular. The plagioclase is subhedral with the dense polycrystalline twins and belongs to albite. Some aegirine pyroxenes are interstitial between and surrounded by the orthoclase minerals. In addition, the several aegirine pyroxenes are partially replaced by biotite minerals. Nevertheless, the primitive mineral shape of aegirine pyroxenes could be identified.

(2) Medium-grained aegirine gabbro syenite (MAS)

This lithofacies is distributed outward to the FBAS, with an approximately 6 km² outcrop (Figure 2). The rock-forming minerals with sizes of 1–3 mm are orthoclase (75–80%) and aegirine pyroxene (15–20%) with the accessory minerals of the magnetite and zircon

(Figures 3b and 4b). The orthoclase is mostly plate-shaped and is overlapped by clay alteration. The aegirine pyroxene is mostly in a euhedral and subhedral columnar shape, and few are fine-grained distributed and are interstitial between and surrounded by the orthoclase minerals.

(3) Coarse-grained aegirine gabbro syenite (CAS)

The CAS phase is restricted in the margin of the Hongshan complex and covers an area of approximately 30 km² (Figure 2). The rocks are massive and show a coarse-grained texture (Figures 3c and 4c,d). The minerals (3–6 mm in diameters) in these rocks are composed of perthite (orthoclase and albite; 85–90%) and aegirine pyroxene (8–10%), with accessory minerals of apatite, zircon, and magnetite. These perthite minerals show Karnofsky bicrystal and are overlapped by clay minerals. The aegirine pyroxene is a subhedral columnar in shapes and distributes in the interstice between the perthite minerals' interior.

Figure 3. Characteristics of field and hand specimens of the Hongshan complex. (a) The fine-grained biotite aegirine syenite (FBAS) and syenite pegmatite (SP), showing that the fine-grained biotite aegirine syenite (FBAS) is emplaced by the syenite pegmatite (SP); (b) The medium-grained aegirine gabbro syenite (MAS); (c) The coarse-grained aegirine gabbro syenite (CAS); (d) The biotite syenite porphyry (BSP); (e) The vein fine-grained biotite hornblende monzo-diorite (MD) that intruded in syenite; (f) The fine-grained hornblende monzo-gabbro (GD).

(4) Syenite pegmatite (SP)

The lithofacies is enveloped by the FBAS stock and have a vesicle shape (Figures 2 and 3a). The rocks of this phase have massive structure and coarse-grained texture, the rock-

forming minerals with diameters of 5–8 mm are orthoclase (65–70%) and perthite (25–30%) (Figure 4e), with the accessory minerals including apatite and zircon.

Figure 4. Photomicrographs of the Hongshan complex. (a) The FBAS, showing the residual Agt metasomatized by Bi; (b) The MAS, showing the euhedral and subhedral columnar Agt; (c,d) the CAS, showing the residual Agt and the fine-grained Agt; (e) the SP; (f) the BSP; (g) The MD; (h) the GD; Or: orthoclase, Bi: biotite, Pl: plagioclase, Agt: aegirine-augite, Pth: perthite, Hb: hornblende, Mag: magnetite. (b,d) are photographs under plane-polarized light. (a,c,e–h) are photographs under cross-polarized light.

(5) Biotite syenite porphyry (BSP)

The BSP rocks are shallower intrusions and have an irregular outcrop of approximately 1 km² in the Hongshan complex (Figures 2 and 3d). They are massive and porphyritic (Figure 3d). The phenocryst minerals in these rocks are orthoclase (25–30%), plagioclase (15–18%), biotite (10–12%), and the equivalent matrix (40–45%) has a microcrystalline texture (Figure 4f). The accessory minerals are magnetite and zircon.

2.2.2. Fine-Grained Biotite Hornblende Monzo-Diorite (MD)

This lithofacies is mainly distributed in the northern and deep parts of the rock mass and intrudes into syenite and strata in the form of veins. The rocks have a massive structure and euhedral subhedral fine-grained texture (0.5–1 mm in diameters). These rocks are

mainly composed of plagioclase (40–45%), orthoclase (20–25%), amphibole (20–25%), biotite (8–10%) and quartz (3–5%). The accessory minerals are magnetite, zircon, and apatite.

2.2.3. Fine-Grained Hornblende Monzo-Gabbro (GD)

GD dikes are intruded into syenite and are massive and fine-grained with (0.5–1.5 mm in diameters) locally porphyritic texture (Figure 3f). The mineral components are plagioclase (45–50%), amphibole (30–35%), orthoclase (15–20%), and biotite (5–8%) (Figure 4h), with accessory minerals of the magnetite and zircon. Most plagioclase and orthoclase crystals are subhedral and granular and are overlapped by the sericitization and clay alteration. The amphibole minerals have a columnar shape.

3. Samples and Analytical Methods

Fresh and weakly altered syenite, MD, and GD samples were collected from surface and drill core to analyze the whole rock geochemistry, single Zircon U-Pb geochronology, and in situ Hf isotope. The sample location is shown in Figure 2.

3.1. Zircon U-Pb Isotope Analyses

LA-ICP-MS completed zircon U-Pb dating in the Key Laboratory of Mineral Resources Evaluation in Northeast Asia, Ministry of Land and Resources, Jilin University, Changchun, China. See [40] for the specific experimental test process. The laser ablation system is the GeoLasPro 193 nm ArF excimer laser produced by the German COMPEX company. The Agilent 7900 ICP-MS instrument is used in conjunction with the laser. Helium was used as the carrier gas of denudation material in the experiment. The instrument is optimized by using synthetic silicate glass standard reference material NIST610. In situ U-Pb analysis of zircon was carried out by the 91,500 standard zircon external correction method. The laser beam spot for sample analysis was 32 μm in diameter. Isotopic ratios and age values were calculated by GLITTER and Isoplot software. The results were corrected for common lead according to the method of [41].

3.2. Major and Trace Elements Analyses of Whole Rock

The whole rock major and trace test of the samples in this paper was completed in the Beijing Research Institute of Uranium Geology, Beijing, China. The main elements were analyzed by X-ray fluorescence with Rigaku Rix 2100 spectrometer, and the analysis uncertainty was 1–5%. The trace elements were analyzed by PEE lan 6000 ICP-MS, and the analysis uncertainty was 1–3%. International reference materials BHVO-1, BCR-2, and AGV-1 are used as test standard samples. The detailed experimental method and test flow are shown in Reference [42].

3.3. Zircon Lu-Hf Isotope Analyses

In situ zircon Hf isotope ratio test was completed by LA-MC-ICP-MS in the Wuhan Sample Solution Analytical Technology Co., Ltd, Wuhan, China. The laser ablation system is Geolas HD (Coherent, Santa Clara, CA, USA), and the MC-ICP-MS is Neptune plus (SPSS v8.0, IBM Corp., Armonk, NY, USA). The signal smoothing device is also equipped in the analysis process to improve the isotope ratio test's signal stability and precision [43]. Helium is used as the carrier gas, and a small amount of nitrogen is introduced after the denudation tank to improve the sensitivity of the Hf element [44]. The experiment was carried out in single-point denudation mode. The laser diameter is 44 μm . Refer to [44] for detailed instrument operating conditions and analysis methods.

4. Results

4.1. Zircon U-Pb Dating

The zircon U-Pb data in this study are provided in Table 1, and the representative zircon cathodoluminescence (CL) images and concordia diagrams are shown in Figures 5 and 6.

Table 1. LA-ICP-MS U-Pb zircon data for the Hongshan complex.

	Content (ppm)			Th/U	Isotopic Ratios						Isotopic Ages (Ma)					
	Pb	Th	U		207Pb/206Pb	±1s	207Pb/235U	±1s	206Pb/238U	±1s	207Pb/206Pb	±1s	207Pb/235U	±1s	206Pb/238U	±1s
ZKS002-8-FBAS																
ZKS002-8-1	23	283	1034	0.27	0.04869	0.00128	0.13208	0.00366	0.01969	0.00044	133	30	126	3	126	3
ZKS002-8-2	50	1070	1726	0.62	0.04891	0.00113	0.15944	0.00397	0.02366	0.00053	144	26	150	3	151	3
ZKS002-8-3	10	254	394	0.64	0.05036	0.00175	0.13729	0.00488	0.01979	0.00045	212	43	131	4	126	3
ZKS002-8-4	14	122	246	0.50	0.05268	0.00161	0.34602	0.01091	0.04767	0.00108	315	35	302	8	300	7
ZKS002-8-5	14	455	518	0.88	0.05307	0.00160	0.14435	0.00452	0.01974	0.00045	332	34	137	4	126	3
ZKS002-8-6	108	722	1631	0.44	0.05408	0.00114	0.41988	0.00972	0.05635	0.00125	374	23	356	7	353	8
ZKS002-8-7	95	370	647	0.57	0.06328	0.00137	1.06136	0.02507	0.12172	0.00272	718	22	734	12	740	16
ZKS002-8-8	22	1161	677	1.72	0.05032	0.00144	0.13658	0.00409	0.01970	0.00045	210	32	130	4	126	3
ZKS002-8-9	13	405	477	0.85	0.05017	0.00159	0.13978	0.00458	0.02022	0.00046	203	38	133	4	129	3
ZKS002-8-10	144	156	231	0.67	0.16825	0.00342	10.73467	0.24206	0.46296	0.01035	2540	17	2500	21	2453	46
ZKS002-8-11	44	1735	1392	1.25	0.04863	0.00131	0.14242	0.00404	0.02125	0.00048	130	31	135	4	136	3
ZKS002-8-12	52	74	134	0.55	0.11000	0.00234	4.67566	0.10937	0.30842	0.00693	1799	19	1763	20	1733	34
ZKS002-8-13	13	422	479	0.88	0.04605	0.00240	0.12603	0.00589	0.01985	0.00046		113	121	5	127	3
ZKS002-8-14	48	2927	1393	2.10	0.04852	0.00119	0.13556	0.00358	0.02027	0.00046	125	28	129	3	129	3
ZKS002-8-15	14	480	562	0.85	0.04678	0.00326	0.12572	0.00823	0.01949	0.00046	38	154	120	7	124	3
ZKS002-8-16	15	439	617	0.71	0.04980	0.00149	0.13674	0.00427	0.01992	0.00046	186	35	130	4	127	3
ZKS002-8-17	5	172	187	0.92	0.05307	0.00370	0.14393	0.00994	0.01968	0.00052	332	109	137	9	126	3
ZKS002-8-18	28	800	993	0.81	0.04905	0.00159	0.14322	0.00481	0.02118	0.00049	150	39	136	4	135	3
ZKS002-8-19	9	222	372	0.60	0.04692	0.00309	0.13070	0.00801	0.02020	0.00048	45	145	125	7	129	3
ZKS002-8-20	20	569	769	0.74	0.04871	0.00142	0.13937	0.00428	0.02076	0.00048	134	34	132	4	132	3
ZKS002-8-21	21	650	791	0.82	0.04963	0.00141	0.14255	0.00427	0.02084	0.00048	178	33	135	4	133	3
ZKS002-8-22	15	362	577	0.63	0.04888	0.00184	0.14473	0.00558	0.02148	0.00051	142	48	137	5	137	3
ZKS002-8-23	38	1614	1338	1.21	0.04605	0.00338	0.12897	0.00895	0.02031	0.00049		163	123	8	130	3
ZK3-3-MD																
ZK3-3-1	8	433	253	1.71	0.05000	0.00336	0.14105	0.00936	0.02048	0.00052	195	105	134	8	131	3
ZK3-3-3	6	236	199	1.19	0.04681	0.00370	0.12408	0.00970	0.01924	0.00050	40	122	119	9	123	3
ZK3-3-4	11	685	328	2.09	0.04579	0.00267	0.12582	0.00726	0.01995	0.00048	13	79	120	7	127	3
ZK3-3-5	5	219	165	1.33	0.04669	0.00330	0.13142	0.00921	0.02044	0.00050	33	107	125	8	130	3
ZK3-3-6	9	503	307	1.64	0.05072	0.00258	0.13598	0.00686	0.01947	0.00046	228	73	129	6	124	3
ZK3-3-7	9	383	227	1.69	0.05610	0.00767	0.14943	0.02000	0.01932	0.00055	456	308	141	18	123	3
ZK3-3-8	7	372	227	1.64	0.04722	0.00233	0.12444	0.00611	0.01913	0.00044	60	67	119	6	122	3
ZK3-3-9	5	256	177	1.44	0.05053	0.00351	0.13379	0.00919	0.01923	0.00049	219	110	127	8	123	3
ZK3-3-10	9	621	297	2.09	0.05051	0.00235	0.13280	0.00615	0.01909	0.00044	219	65	127	6	122	3
ZK3-3-11	9	546	278	1.96	0.05070	0.00228	0.13125	0.00589	0.01880	0.00043	227	62	125	5	120	3
ZK3-3-12	4	170	124	1.37	0.04436	0.00429	0.11917	0.01141	0.01950	0.00052	52	159	114	10	124	3
ZK3-3-13	9	490	281	1.74	0.05121	0.00242	0.14353	0.00678	0.02034	0.00047	250	67	136	6	130	3
ZK3-3-14	7	312	240	1.30	0.04870	0.00237	0.13068	0.00636	0.01948	0.00046	133	70	125	6	124	3
ZK3-3-15	9	512	274	1.87	0.05516	0.00243	0.14815	0.00653	0.01949	0.00045	419	58	140	6	124	3
ZK3-3-16	7	357	228	1.57	0.05886	0.00308	0.15946	0.00830	0.01966	0.00047	562	72	150	7	126	3

Table 1. Cont.

	Content (ppm)			Th/U	Isotopic Ratios						Isotopic Ages (Ma)					
	Pb	Th	U		207Pb/206Pb	±1s	207Pb/235U	±1s	206Pb/238U	±1s	207Pb/206Pb	±1s	207Pb/235U	±1s	206Pb/238U	±1s
ZK3-3-17	10	572	296	1.93	0.05319	0.00252	0.14689	0.00695	0.02004	0.00047	337	65	139	6	128	3
ZK3-3-18	13	845	320	2.64	0.05171	0.00251	0.14055	0.00682	0.01972	0.00047	273	68	134	6	126	3
ZK3-3-19	8	421	250	1.69	0.05183	0.00280	0.14372	0.00773	0.02011	0.00049	278	79	136	7	128	3
ZK3-3-20	5	202	152	1.32	0.04605	0.00394	0.12373	0.01014	0.01949	0.00048		189	118	9	124	3
ZK3-3-21	6	339	199	1.70	0.05104	0.00271	0.13302	0.00705	0.01890	0.00046	243	78	127	6	121	3
ZK3-3-22	7	400	239	1.67	0.05208	0.00261	0.13646	0.00685	0.01900	0.00045	289	72	130	6	121	3
ZK3-6-MG																
ZK3-6-1	17	1044	532	1.96	0.05086	0.00128	0.13852	0.00348	0.01976	0.00024	234	36	132	3	126	2
ZK3-6-2	16	860	516	1.67	0.05256	0.00138	0.14097	0.00370	0.01946	0.00024	310	37	134	3	124	2
ZK3-6-3	17	934	565	1.65	0.04824	0.00123	0.13100	0.00335	0.01970	0.00024	111	38	125	3	126	2
ZK3-6-4	22	1013	811	1.25	0.05014	0.00116	0.13189	0.00308	0.01909	0.00023	201	32	126	3	122	1
ZK3-6-5	25	1753	669	2.62	0.04605	0.00183	0.12343	0.00468	0.01944	0.00023		84	118	4	124	1
ZK3-6-6	12	497	457	1.09	0.04632	0.00228	0.12151	0.00578	0.01903	0.00024	14	106	116	5	122	2
ZK3-6-7	25	1580	777	2.03	0.04819	0.00111	0.12977	0.00300	0.01954	0.00023	109	33	124	3	125	1
ZK3-6-8	13	456	407	1.12	0.04605	0.00300	0.11807	0.00750	0.01860	0.00026		143	113	7	119	2
ZK3-6-9	18	886	596	1.49	0.05109	0.00129	0.13747	0.00347	0.01953	0.00024	245	36	131	3	125	2
ZK3-6-10	5	165	182	0.91	0.05171	0.00250	0.13855	0.00660	0.01944	0.00028	273	83	132	6	124	2
ZK3-6-11	11	542	370	1.46	0.05024	0.00151	0.13479	0.00402	0.01947	0.00024	206	46	128	4	124	2
ZK3-6-12	14	755	436	1.73	0.05005	0.00354	0.13520	0.00939	0.01959	0.00027	197	162	129	8	125	2
ZK3-6-14	5	218	192	1.14	0.05287	0.00249	0.14217	0.00661	0.01952	0.00028	323	79	135	6	125	2
ZK3-6-15	8	343	258	1.33	0.04605	0.00201	0.12356	0.00518	0.01946	0.00025		93	118	5	124	2
ZK3-6-16	7	293	245	1.20	0.04638	0.00196	0.12967	0.00541	0.02029	0.00027	17	63	124	5	129	2
ZK3-6-17	17	1262	473	2.67	0.05005	0.00142	0.13474	0.00381	0.01954	0.00024	197	43	128	3	125	2
ZK3-6-18	19	1168	572	2.04	0.05016	0.00140	0.13713	0.00381	0.01985	0.00024	202	42	130	3	127	2
ZK3-6-19	21	1184	730	1.62	0.04976	0.00129	0.13365	0.00346	0.01950	0.00024	184	38	127	3	124	2
ZK3-6-21	5	214	184	1.17	0.04605	0.00221	0.12249	0.00563	0.01929	0.00027		103	117	5	123	2

Figure 5. (a–c) Cathodoluminescence (CL) images of selected zircons from the FBAS, MD, and GD, respectively. The solid lines and the dash lines represent the locations of analysis spots used for U–Pb dating and Hf isotopic analyses, respectively.

4.1.1. FBAS (ZKS002-8)

The zircon grains from FBAS show euhedral biconical or columnar crystals (Figure 5a). They are 100–300 µm in length, 50–100 µm in width, and the ratio of length to width is between 2:1 and 3:1. According to the CL image and age data of 23 zircons, two groups can be identified:

Group 1: The Th/U ratios are 0.44–0.67. These zircons are generally round or oblate in shape, and their absorption is uneven. Some zircons have developed a white hydrothermal ring zone at the edge, indicating that they have experienced some degree of transportation and varying degrees of later hydrothermal activity. According to the concordant ages (6 grains), they formed in the Neoproterozoic (2540 ± 17 Ma), Paleoproterozoic (1799 ± 19 Ma), Neoproterozoic (718 ± 22 Ma), Carboniferous (353 ± 8 Ma and 300 ± 7 Ma), and Middle Jurassic (151 ± 3 Ma).

Group 2: These grains feature clear oscillatory zones in the CL images. The U contents are 394–1392 ppm, the Th contents are 172–2926 ppm, and the Th/U ratios are 0.27–2.10. The $^{206}\text{Pb}/^{238}\text{U}$ ages of 17 zircons range from 137 to 124 Ma, with a weighted average age of 129.3 ± 2.0 Ma (MSWD = 1.7) (Figure 6b).

4.1.2. MD (ZK3-3)

The zircon grains are mostly transparent to translucent and subhedral to euhedral columnar crystals in the CL images (Figure 5b). They are 50–150 µm long and 30–80 µm wide, and the ratio of length to width is between 1:1 and 3:1. There are clear oscillatory zones in the interior. The 21 analyzed zircons contain 124–319 ppm U, 169–684 ppm Th, and Th/U ratios of 1.16–2.64. The 21 data points are concentrated on or near the concordia line, and the weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of the zircon grains is 124.8 ± 1.3 Ma (MSWD = 1.12) (Figure 6d).

4.1.3. GD (ZK3-6)

CL images show that the zircon grains from the GD are translucent, subhedral to euhedral, and columnar. The zircons contain well-developed oscillatory zones with the internal structural characteristics of magmatic zircons. The 19 analyzed zircons contain 182–777 ppm U, 214–1753 ppm Th and Th/U ratios of 0.91–2.67. The weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of the zircon grains is 124.1 ± 0.9 Ma (MSWD = 1.3) (Figure 6f).

Figure 6. (a,c,e) U-Pb concordia diagrams of the FBAS, MD, and GD, respectively; (b,d,f) weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages diagrams of the FBAS, MD, and GD, respectively. MSWD= mean square weighted deviation.

4.2. Major Elements, Trace Elements, and REEs

Eighteen samples, including twelve syenite samples (FBAS, MAS, CAS, SP, and BSP), four MD samples, and two GD samples from the Hongshan complex, were analyzed for geochemistry. The results are listed in Table 2.

Table 2. Major (wt.%) and trace (ppm) elements for the Hongshan complex.

Sample No.	ZKS002-8-1	ZKS002-8-2	ZKS002-11-1	ZKS002-11-2	ZKS002-14	ZKS002-24-1	ZKS002-24-2	PM03-27-1	PM03-23-1
Rock Type	FBAS (Fine-Grained Biotite Aegirine Syenite)		BAS(Medium-Grained Aegirine Gabbro Syenite)			CAS (Coarse-Grained Aegirine Gabbro Syenite)		SP (Syenite Pegmatite)	
Major element (wt.%)									
SiO ₂	60.92	61.11	64.88	62.11	64.84	62.03	61.81	63.75	63.90
TiO ₂	0.58	0.59	0.26	0.34	0.26	0.51	0.54	0.39	0.34
Al ₂ O ₃	16.38	16.52	18.16	16.80	18.08	17.36	17.13	19.10	18.91
Fe ₂ O ₃	3.93	3.62	1.53	3.29	1.42	2.84	3.22	2.60	2.44
FeO	2.18	2.36	0.87	1.84	0.76	1.44	1.55	0.10	0.18
MnO	0.16	0.15	0.05	0.12	0.05	0.10	0.11	0.02	0.03
MgO	1.86	1.75	0.39	1.05	0.28	0.93	0.99	0.15	0.09
CaO	2.30	1.98	1.05	1.68	1.00	2.29	2.33	0.48	0.51
Na ₂ O	8.60	8.70	7.19	6.74	6.72	6.02	5.99	7.07	6.77
K ₂ O	1.60	1.78	5.12	5.11	6.08	5.46	5.32	5.26	5.66
P ₂ O ₅	0.31	0.30	0.04	0.19	0.05	0.24	0.19	0.07	0.11
LOI	1.04	1.00	0.29	0.54	0.32	0.45	0.46	0.71	0.77
Total	99.86	99.86	99.83	99.81	99.85	99.67	99.64	99.70	99.71
K ₂ O + Na ₂ O	10.20	10.48	12.31	11.85	12.80	11.48	11.31	12.33	12.44
A/CNK	0.82	0.83	0.94	0.85	0.93	0.87	0.86	1.05	1.04
A/NK	1.03	1.02	1.05	1.01	1.03	1.10	1.10	1.10	1.09
^T Fe ₂ O ₃	6.35	6.24	2.50	5.34	2.26	4.44	4.94	2.71	2.64
Mg [#]	36.7	35.7	23.6	28.0	19.7	29.3	28.4	9.6	6.4
Trace element (ppm)									
Sc	10.20	5.92	1.46	3.00	1.58	5.20	4.66	1.47	2.06
V	170.00	175.00	74.90	195.00	64.80	129.00	166.00	89.91	94.00
Cr	9.54	8.49	1.91	7.40	2.72	3.84	3.34	3.85	6.20
Co	8.83	9.59	3.20	7.63	2.84	7.15	8.08	3.10	2.70
Ni	8.39	8.76	1.93	15.90	9.52	9.49	10.10	2.65	2.17
Cu	38.50	38.10	36.90	107.00	5.52	38.60	20.30	238.77	207.46
Zn	134.00	133.00	51.10	125.00	41.00	80.90	90.90	93.13	64.07
Ga	25.50	25.70	27.90	25.50	25.30	21.20	22.40	29.72	31.57
Rb	48.10	53.90	110.00	124.00	145.00	107.00	104.00	130.60	114.48
Sr	475.00	487.00	843.00	715.00	726.00	1592.00	1737.00	641.14	775.34
Y	17.30	22.10	8.03	10.20	7.22	16.40	17.30	16.10	13.61
Zr	325.00	322.00	241.00	316.00	301.00	88.20	97.10	399.76	569.61
Nb	17.70	16.30	11.30	8.61	8.45	9.23	9.91	17.07	22.27
Cs	0.56	0.66	0.39	1.17	0.88	0.74	0.71	1.00	0.97
Ba	189.00	246.00	482.00	391.00	466.00	1188.00	1259.00	847.62	788.84
La	22.80	24.70	11.50	16.40	19.00	34.20	33.80	39.92	39.39
Ce	48.00	58.90	25.00	29.60	32.40	63.60	63.50	48.98	55.54
Pr	6.15	7.81	3.02	3.58	3.43	7.74	7.98	5.17	5.59
Nd	24.10	30.40	11.00	13.40	11.80	30.50	31.40	17.05	17.54
Sm	4.83	6.17	1.93	2.38	2.01	5.52	5.87	2.80	2.79

Table 2. Cont.

Eu	1.30	1.73	0.77	0.82	0.75	1.96	2.07	1.11	1.08
Gd	4.31	5.44	1.84	2.29	1.92	4.94	5.03	2.80	2.63
Tb	0.67	0.83	0.28	0.34	0.28	0.69	0.74	0.39	0.36
Dy	3.45	4.47	1.45	1.82	1.41	3.39	3.63	2.26	2.08
Ho	0.66	0.84	0.29	0.36	0.26	0.60	0.64	0.46	0.43
Er	1.89	2.29	0.88	1.11	0.75	1.64	1.75	1.46	1.36
Tm	0.34	0.38	0.18	0.23	0.16	0.26	0.28	0.26	0.24
Yb	2.19	2.38	1.22	1.59	0.94	1.61	1.77	1.61	1.59
Lu	0.35	0.37	0.18	0.27	0.13	0.22	0.25	0.30	0.27
Hf	8.40	7.97	6.05	7.55	6.71	2.66	3.07	10.61	14.22
Ta	1.12	1.38	0.42	0.44	0.38	0.56	0.59	0.61	0.66
Pb	15.90	16.90	25.30	21.30	23.50	25.40	26.30	29.55	23.56
Th	12.80	9.96	6.98	7.66	2.71	3.11	3.46	15.96	18.06
U	2.94	2.88	2.08	2.28	0.90	0.86	0.98	3.92	5.06
ΣREE	121.04	146.71	59.54	74.19	75.24	156.87	158.71	124.58	130.89
LREE	107.18	129.71	53.22	66.18	69.39	143.52	144.62	115.04	121.94
HREE	13.86	17.00	6.32	8.01	5.85	13.35	14.09	9.54	8.95
LREE/HREE	7.73	7.63	8.42	8.26	11.86	10.75	10.26	12.06	13.62
(La/Yb) _N	7.47	7.44	6.76	7.40	14.50	15.24	13.70	17.77	17.75
δEu	0.87	0.91	1.25	1.07	1.17	1.15	1.16	1.21	1.22
Sample No.	ZK32-1-1	ZKN001-1	ZKN001-2	GY-3-1	GY-3-2	ZK3-3-1	ZK3-3-2	ZK3-6-1	ZK3-6-2
Rock Type	BSP (Biotite Syenite Porphyry)			MD (Fine-Grained Biotite Hornblende Monzo-Diorite)			GD (Fine-Grained Hornblende Monzo-Gabbro)		
Major element (wt.%)									
SiO ₂	58.53	62.40	63.23	56.15	56.10	57.75	57.50	48.98	48.94
TiO ₂	0.54	0.54	0.51	0.77	0.73	0.70	0.71	1.03	1.06
Al ₂ O ₃	16.43	17.13	17.04	15.26	14.25	15.76	15.60	14.46	14.25
Fe ₂ O ₃	3.30	3.29	2.43	3.94	4.81	3.58	3.40	4.98	4.71
FeO	2.15	1.52	1.06	3.08	3.05	3.62	3.65	5.82	6.02
MnO	0.09	0.04	0.08	0.12	0.11	0.11	0.11	0.15	0.16
MgO	2.56	1.05	0.81	4.37	4.59	4.06	4.04	7.84	8.16
CaO	1.84	0.73	1.04	5.74	4.80	5.07	5.20	8.36	8.59
Na ₂ O	3.23	5.82	6.16	4.14	3.92	4.65	4.76	3.89	3.68
K ₂ O	6.20	6.10	5.76	4.74	5.49	2.68	2.77	1.44	1.50
P ₂ O ₅	0.43	0.21	0.14	0.52	0.58	0.30	0.30	0.40	0.41
LOI	4.43	1.00	1.59	0.96	1.33	1.44	1.70	2.31	2.22
Total	99.73	99.83	99.85	99.79	99.76	99.72	99.74	99.66	99.70
K ₂ O + Na ₂ O	9.43	11.92	11.92	8.88	9.41	7.33	7.53	5.33	5.18
A/CNK	1.07	0.98	0.93	0.68	0.67	0.80	0.77	0.62	0.61
A/NK	1.37	1.06	1.04	1.28	1.15	1.49	1.44	1.82	1.86
^T Fe ₂ O ₃	5.69	4.98	3.61	7.36	8.20	7.60	7.46	11.45	11.40
Mg [#]	47.1	29.5	30.8	54.0	52.6	51.4	51.8	57.6	58.6

Table 2. Cont.

Trace element (ppm)									
Sc	8.84	4.80	2.20	16.40	20.80	17.80	12.90	24.30	24.30
V	124.00	102.00	76.00	163.00	167.00	147.00	155.00	259.00	255.00
Cr	31.80	4.51	2.34	66.00	96.40	45.90	35.40	178.00	163.00
Co	16.60	7.33	5.12	23.30	19.80	16.50	17.30	35.60	36.50
Ni	29.41	11.10	8.11	35.00	52.70	20.60	22.60	81.00	85.20
Cu	48.20	55.70	57.70	26.20	43.60	8.37	11.40	18.20	19.40
Zn	64.40	73.90	50.00	54.30	56.80	43.90	45.30	68.40	68.60
Ga	23.20	25.70	25.10	20.80	19.20	18.70	19.80	20.30	18.70
Rb	206.00	245.00	183.00	159.00	161.00	50.90	55.50	26.60	23.40
Sr	791.00	467.00	356.00	840.00	784.00	884.00	892.00	1937.00	1496.00
Y	15.30	18.70	20.40	19.00	17.50	17.70	18.50	20.10	19.90
Zr	239.00	417.00	500.00	205.00	187.00	83.00	94.70	74.70	76.00
Nb	11.50	21.40	25.40	9.26	8.87	6.72	7.02	5.17	4.92
Cs	14.59	2.82	1.30	4.60	3.96	0.51	0.56	0.95	0.47
Ba	778.00	516.00	325.00	690.00	813.00	1269.00	1375.00	791.00	699.00
La	29.70	41.20	43.90	30.40	30.30	26.60	27.80	18.70	18.00
Ce	55.30	70.40	80.60	66.20	60.40	50.70	54.80	41.10	38.60
Pr	6.49	8.04	8.87	8.50	7.29	6.30	6.80	5.69	5.54
Nd	25.00	28.20	30.30	34.80	29.20	25.10	26.80	25.80	24.90
Sm	4.56	4.97	5.23	6.49	5.55	4.69	4.97	5.40	5.18
Eu	1.43	1.35	1.22	2.04	1.78	1.72	1.85	1.84	1.79
Gd	4.11	4.84	5.06	5.59	4.94	4.33	4.54	4.84	4.79
Tb	0.59	0.67	0.72	0.80	0.70	0.64	0.68	0.76	0.76
Dy	2.95	3.48	3.81	3.97	3.52	3.47	3.60	4.09	4.06
Ho	0.55	0.67	0.75	0.72	0.63	0.67	0.69	0.76	0.77
Er	1.56	1.97	2.26	1.94	1.70	1.83	1.88	2.06	2.09
Tm	0.28	0.34	0.40	0.32	0.29	0.30	0.31	0.33	0.33
Yb	1.75	2.23	2.65	1.98	1.76	1.81	1.91	2.00	1.96
Lu	0.25	0.34	0.40	0.29	0.25	0.27	0.28	0.29	0.28
Hf	5.75	10.70	13.30	5.19	4.63	2.59	2.93	2.27	2.39
Ta	1.18	1.40	1.70	0.55	0.64	0.44	0.49	0.35	0.28
Pb	22.20	20.70	15.70	11.60	16.80	8.39	7.76	5.10	5.86
Th	11.00	20.00	24.80	6.79	7.51	3.45	3.39	1.51	1.42
U	3.42	5.15	6.74	2.14	2.13	0.96	1.07	0.48	0.41
ΣREE	134.52	168.70	186.17	164.04	148.31	128.43	136.91	113.66	109.05
LREE	122.48	154.16	170.12	148.43	134.52	115.11	123.02	98.53	94.01
HREE	12.04	14.54	16.05	15.61	13.79	13.32	13.89	15.13	15.04
LREE/HREE	10.17	10.60	10.60	9.51	9.75	8.64	8.86	6.51	6.25
(La/Yb) _N	12.17	13.25	11.88	11.01	12.35	10.54	10.44	6.71	6.59
δEu	1.01	0.84	0.73	1.04	1.04	1.17	1.19	1.10	1.10

A/NK = molar Al_2O_3 / ($\text{Na}_2\text{O} + \text{K}_2\text{O}$); A/CNK = molar Al_2O_3 / ($\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO}$); $\text{Mg}^\# = 100 \times \text{molar Mg} / (\text{Mg} + \text{Fe})$; $\delta\text{Eu} = \text{Eu} / [(\text{Sm} + \text{Gd})/2]$.

4.2.1. Syenites (FBAS, MAS, CAS, SP, and BSP)

As noted before, the syenite facies includes FBAS, MAS, CAS, SP, and BSP. The element contents of these subfacies do not vary greatly from the FBAS to the BSP. They have similar geochemical characteristics: (1) The rocks have high concentrations of SiO_2 (60.92–64.88 wt%) and total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) (10.2–13.0 wt%), and they plot in the syenite field in the TAS diagram [45] (Figure 7a). In the diagram of SiO_2 -AR, the samples fall in the alkaline area. (2) In the ANK-ACNK diagram, the component points are concentrated in the metaluminous and peraluminous fields. (3) They are enriched in light REEs (LREEs) and large ion lithophile elements (LILEs), such as Rb (48.1–245 ppm), Sr (356–1737 ppm), Th (2.7–24.8 ppm), U (0.86–6.74 ppm), and K (6720–27004 ppm), and are relatively depleted in heavy REEs (HREEs) and high field strength elements (HFSEs), such as Nb (8.45–25.40 ppm), Ta (0.38–1.70 ppm) and Ti (1566–3576 ppm) (Figure 8a,b). (4) With magma evolution, the contents of SiO_2 , Al_2O_3 , K_2O , and Nb/Ta and the LREEs/HREEs ratios increased, and the contents of CaO, Na_2O , Fe_2O_3 , MgO, TiO_2 , and P_2O_5 and the Sm/Nd ratio decreased to varying degrees (Figure 9).

Figure 7. (a) TAS diagram for classification [45]; (b) SiO_2 versus AR classification diagram [46], AR: $[\text{Al}_2\text{O}_3 + \text{CaO} + (\text{Na}_2\text{O} + \text{K}_2\text{O})] / [\text{Al}_2\text{O}_3 + \text{CaO} - (\text{Na}_2\text{O} + \text{K}_2\text{O})]$ (wt% is the percentage calculated after the loss on ignition is removed); (c) ANK versus ACNK classification diagram [47], ANK = molar $\text{Al}_2\text{O}_3 / (\text{Na}_2\text{O} + \text{K}_2\text{O})$, ACNK = molar $\text{Al}_2\text{O}_3 / (\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO})$; (d) K_2O versus Na_2O classification diagram [48].

Figure 8. (a,c) Chondrite-normalized REE patterns for the Hongshan complex; (b,d) Primitive mantle-normalized trace element patterns. Chondrite and PM values are from Reference [49].

4.2.2. Diorite and Gabbro

(1) MD

The MD shows low concentrations of SiO_2 (56.10–57.75 wt%) and high concentrations of MgO (4.04–4.59 wt%), as well as relatively high magnesium numbers ranging from 51.4 to 54.0 [$\text{Mg}^\# = \text{molar } 100 \times \text{MgO} / (\text{MgO} + \text{FeO})$]. They have total alkali ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) contents of 7.33–9.41 wt% and plots in the monzonite field in the TAS diagram (Figure 7a). In the SiO_2 -AR diagram, the samples fall in the calc-alkaline and alkaline fields (Figure 7b). In the ANK-ACNK diagram, the component points fall in the metaluminous area (Figure 7c). The MD has relatively high K_2O contents and relatively low P_2O_5 contents. The MD's total REE (ΣREE) contents range from 121.04–146.71 ppm, and the REE distribution curve shows an obvious right-sloping pattern. The rocks are characterized by LREE enrichment, moderate fractionation between LREEs and HREEs ($(\text{La}/\text{Yb})_N = 10.4\text{--}12.4$), and slight or no negative Eu anomalies ($\delta\text{Eu} = 0.85\text{--}1.20$). In the primitive mantle-normalized spidergram, these rocks show enrichment in LILEs, such as Rb (50.9–161 ppm), Sr (784–892 ppm), Ba (690–1375 ppm), Th (3.39–7.51 ppm), and U (0.96–2.14 ppm), and depletion in HFSEs, such as Nb (6.72–9.26 ppm), Ta (0.44–0.64 ppm), Zr (83–205 ppm) and Hf (2.59–5.19 ppm).

(2) GD

The GD contains 48.94–48.98 wt% SiO_2 , 11.40–11.45 wt% Fe_2O_3 , 1.03–1.06 wt% TiO_2 , 7.84–8.16 wt% MgO , 1.44–1.50 wt% K_2O , and 3.68–4.89 wt% Na_2O and has $\text{Mg}^\#$ values of 57.6–58.6. These samples correspond to the monzo-gabbro basalt series in the TAS diagram (Figure 7a). The REE and trace element characteristics of the GD are similar to those of the MD. Compared with the MD, the GD has a lower fractionation degree between LREEs and HREEs ($(\text{La}/\text{Yb})_N = 6.6\text{--}6.7$) (Figure 8c). In the primitive mantle-normalized spidergram, these rocks show enrichment in LILEs, such as Rb (23.4–26.6 ppm), Sr (1496–1937 ppm), and

Ba (699–791 ppm), and depletion in HFSEs, such as Nb (4.92–5.17 ppm), Ta (0.28–0.35 ppm), Zr (74.7–77.0 ppm) and Hf (2.27–2.39 ppm) (Figure 8d).

Figure 9. Harker diagrams for the Hongshan complex.

4.3. Zircon Lu-Hf Isotopes

The in situ Hf isotope analysis results of zircons from the FBAS, MD, and GD from the Hongshan complex are listed in Table 3 and presented in an $\epsilon\text{Hf}(t)$ vs. age diagram in Figure 10a.

Table 3. In situ zircon Hf isotopic compositions for the Hongshan complex.

No.	t (Ma)	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	1s	$\epsilon_{\text{Hf}}(0)$	$\epsilon_{\text{Hf}}(t)$	$T_{\text{DM1}}(\text{Hf})$	$T_{\text{DM2}}(\text{Hf})$	$f_{\text{Lu/Hf}}$
ZKS002-8-FBAS										
ZKS002-8-3	126	0.025425	0.001148	0.282361	0.000020	−14.53	−11.80	1264	2684	−0.97
ZKS002-8-5	126	0.035780	0.001419	0.282338	0.000010	−15.3	−12.64	1306	2760	−0.96
ZKS002-8-8	126	0.084008	0.003044	0.282353	0.000010	−14.82	−12.25	1343	2724	−0.91
ZKS002-8-9	129	0.031872	0.001309	0.282319	0.000009	−16.02	−13.31	1329	2819	−0.96
ZKS002-8-10	2540	0.012299	0.000511	0.281326	0.000008	−51.12	4.99	2655	2804	−0.98
ZKS002-8-11	136	0.025782	0.000891	0.282178	0.000008	−21.01	−18.27	1511	3262	−0.97
ZKS002-8-12	1799	0.003867	0.000135	0.281530	0.000008	−43.92	−4.04	2358	3091	−1.00
ZKS002-8-13	127	0.028804	0.001222	0.282304	0.000008	−16.55	−13.83	1347	2866	−0.96
ZKS002-8-16	127	0.038991	0.001456	0.282362	0.000009	−14.49	−11.78	1273	2683	−0.96
ZKS002-8-16	127	0.014007	0.000542	0.282350	0.000007	−14.9	−12.14	1260	2715	−0.98
ZKS002-8-17	126	0.024920	0.000937	0.282359	0.000019	−14.60	−11.85	1260	2689	−0.97
ZKS002-8-20	133	0.031035	0.001327	0.282333	0.000013	−15.5	−12.82	1310	2775	−0.96
ZKS002-8-21	132	0.029445	0.001248	0.282350	0.000008	−14.91	−12.19	1283	2719	−0.96
ZKS002-8-22	137	0.019798	0.000915	0.282325	0.000008	−15.81	−13.06	1307	2797	−0.97
ZKS002-8-23	130	0.034775	0.001211	0.282321	0.000011	−15.95	−13.23	1323	2812	−0.96
ZK3-3-MD										
ZK3-3-3	123	0.055182	0.002338	0.282124	0.000018	−22.90	−20.38	1648	3445	−0.93
ZK3-3-5	130	0.070482	0.002922	0.282123	0.000022	−22.97	−20.49	1677	3455	−0.91
ZK3-3-7	123	0.064161	0.002669	0.282070	0.000016	−24.84	−22.35	1743	3619	−0.92
ZK3-3-9	123	0.082849	0.003469	0.282112	0.000020	−23.33	−20.90	1719	3490	−0.90
ZK3-3-10	122	0.076025	0.003167	0.282145	0.000022	−22.16	−19.7	1655	3385	−0.90
ZK3-3-12	124	0.062638	0.002612	0.282153	0.000025	−21.90	−19.40	1619	3358	−0.92
ZK3-3-13	130	0.062195	0.002554	0.282180	0.000024	−20.92	−18.42	1577	3271	−0.92
ZK3-3-16	126	0.091824	0.003736	0.282077	0.000021	−24.57	−22.17	1784	3602	−0.89
ZK3-3-17	128	0.087753	0.003621	0.282157	0.000036	−21.75	−19.34	1659	3351	−0.89
ZK3-3-19	128	0.088719	0.003657	0.282183	0.000042	−20.84	−18.43	1623	3271	−0.89
ZK3-6-GD										
ZK3-6-1	126	0.085878	0.003594	0.282145	0.000025	−22.18	−19.76	1676	3389	−0.89
ZK3-6-2	124	0.102319	0.004309	0.282184	0.000022	−20.80	−18.44	1651	3271	−0.87
ZK3-6-3	126	0.115486	0.004769	0.282186	0.000025	−20.73	−18.40	1670	3267	−0.86
ZK3-6-5	124	0.138117	0.005540	0.282185	0.000024	−20.76	−18.50	1710	3275	−0.83
ZK3-6-6	122	0.076656	0.003628	0.282196	0.000022	−20.38	−17.96	1602	3229	−0.89
ZK3-6-8	119	0.049361	0.002223	0.282150	0.000020	−21.99	−19.45	1606	3363	−0.93
ZK3-6-9	125	0.107329	0.004582	0.282214	0.000022	−19.72	−17.38	1617	3176	−0.86
ZK3-6-12	125	0.064189	0.002802	0.282172	0.000021	−21.23	−18.75	1600	3299	−0.92
ZK3-6-16	129	0.055839	0.002437	0.282186	0.000020	−20.72	−18.21	1563	3252	−0.93
ZK3-6-17	125	0.131636	0.005386	0.282203	0.000021	−20.13	−17.85	1674	3218	−0.84
ZK3-6-19	124	0.132792	0.005927	0.282227	0.000022	−19.26	−17.04	1663	3144	−0.82
ZK3-6-21	123	0.070731	0.002944	0.282137	0.000018	−22.47	−19.99	1658	3410	−0.91

Figure 10. (a) $\epsilon_{\text{Hf}}(t)$ versus crystallization age of zircons from the Hongshan complex [50]; (b) Frequency distributions of the T_{DM2} of zircons from the Hongshan complex.

4.3.1. FBAS (ZKS002-8)

The $^{176}\text{Hf}/^{177}\text{Hf}$ values of a Neoproterozoic magmatic zircon grain (~2540 Ma, 1 grain) and a Paleoproterozoic magmatic zircon grain (~1799 Ma, 1 grain) from the FBAS are 0.281302 and 0.281525, respectively, and their $\epsilon\text{Hf}(t)$ values are 5.0 and −4.0. Their single-stage Hf model ages (T_{DM1}) are 2.66 Ga and 2.36 Ga, and the two-stage Hf model ages (T_{DM2}) are 2.80 Ga and 3.09 Ga, respectively. The Mesozoic magmatic zircon grains (~129.1 Ma, 13 grains) have a $^{176}\text{Hf}/^{177}\text{Hf}$ range from 0.282176 to 0.282359. The T_{DM1} values range from 1.25 to 1.51 Ga (Avg. = 1.32 Ga), and the T_{DM2} values range from 2.68–3.26 Ga (Avg. = 2.79 Ga). The $\epsilon\text{Hf}(t)$ values are all negative, ranging from −18.3 to −11.8, with a mean value of −13.0.

4.3.2. MD (ZK3-3)

The initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of ten zircon grains from the MD vary from 0.282063 to 0.282174. The $\epsilon\text{Hf}(t)$ values are all negative and range between −22.3 and −18.4, with an average value of −20.2. The T_{DM1} values range from 1.58 to 1.78 Ga (Avg. = 1.67 Ga), and the T_{DM2} values range from 3.27–3.62 Ga (Avg. = 3.42 Ga).

4.3.3. GD (ZK3-6)

The GD's zircon Hf isotope analysis results show that the initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of twelve zircon grains vary from 0.282130 to 0.282214. The T_{DM1} values range from 1.56 to 1.71 Ga (mean: 1.64 Ga), and the T_{DM2} values range from 3.14–3.41 Ga (Avg. = 3.27 Ga). The $\epsilon\text{Hf}(t)$ values are concentrated between −20.0 and −17.0 (Avg. = −18.5).

5. Discussion

5.1. Emplacement Time and Magmatism Stage

The southern part of the Taihang Mountains developed Mesozoic regional alkaline and calc-alkaline magmatic activities with a peak period at 124–154 Ma based on the data of the isotopic geochronology [14,39], and most volcanic events are concentrated at 127–138 Ma [51]. In the Handan area (Figure 11), we collected 20 age data sets from Pingshun rocks, Dongye rocks, Fushan rocks, Guzhen rocks, Kuangshancun rocks, and Hongshan complex. They are derived from zircon SHRIMP U-Pb ages or zircon LA U-Pb ages of syenite, monzonite, diorite, and gabbro. We can divide them into two peaks of magmatic activity: (1) 135–130 Ma monzonitic-syenite magmatism and (2) ~125 Ma gabbro-diorite magmatism. In this study, the weighted mean ages of zircon grains from the FBAS are 129.3 ± 2.0 Ma (sample ZKS002-8). Zircon grains show typical growth zoning and euhedral grain morphology, suggesting that the ages represent the timing of emplacement of the FBAS. The MD magmatic crystallization age is 124.8 ± 1.3 Ma, and the GD magmatic crystallization age is 124.1 ± 0.9 Ma. The geochronological data are consistent with the emplacement relationship observed in the field, and the MD and GD are the products of another phase of magmatism after syenite facies emplacement. Furthermore, these ages are consistent with the emplacement age of the syenite (135–130 Ma), diorite, and gabbro (~125 Ma) in the Handan area. The above discussion indicates that the Hongshan alkaline complex has experienced at least two different magmatic events: the early syenite magmatic event and the late diorite and gabbro magmatic event. The gap between the two stages of magmatism was approximately 5 Ma, and both events occurred in the Early Cretaceous in the Mesozoic.

Figure 11. The ages of Mesozoic rocks from the Handan area. G: Gabbro, D: Diorite, MG: monzo-gabbro, MD: monzo-diorite, M: monzonite, CS: coarse-grained syenite, MS: medium-grained syenite, FS: fine-grained.

5.2. Petrogenesis

The geologic and geochronologic characteristics of the Hongshan complex suggest a multistage plutonic and hypabyssal alkaline complex. The syenite, MD, and GD have independent geochemical characteristics. Furthermore, gabbro-diorite magmatism is later than syenite magmatism. These characteristics are difficult to be explained by their origin in the evolution of homologous magma. If they are derived from the same magma evolution, syenite should be from the late magma evolution, and its formation age should be slightly later than gabbro and diorite. This is inconsistent with the dating results. Therefore, we discuss their petrogenesis separately.

5.2.1. Petrogenesis of the Syenites

Petrogenetic models of syenite are diverse, including (1) strong fractional crystallization of mantle-derived basaltic magma [52,53]; (2) partial melting of enriched lithospheric mantle [54,55]; (3) mixing of mantle-derived basaltic magma and crust derived melt [56,57]; and (4) partial melting of thickened continental crust (or partial melting of crustal rocks under high pressure) [58,59]. The syenites from Hongshan are generally high in Al ($\text{Al}_2\text{O}_3 = 16.38\text{--}19.10\%$), high in Sr (356–1737 ppm), and low in Yb (0.94–2.65 ppm) and have high Sr/Y ratios (17.45–100.55). Furthermore, the syenites have relatively low MgO contents (0.09–2.56%) and are depleted in mantle-derived elements, such as Cr (Avg = 7.16 ppm), Co (Avg = 6.85 ppm), and Ni (Avg = 9.79 ppm). It shows the geochemical properties of adakitic rocks associated with thickened lower crust (Figure 12) [60]. Experimental petrology and phase equilibrium studies show that partial melting of normal-thickness continental crust

or the middle-upper part of thickened continental crust (≤ 1.0 GPa, 30–40 km) produces granitic magma, whereas partial melting of the bottom of thickened continental crust (55–60 km) produces syenite magma [61]. Deng (1998) divided trachyte (syenite) into a high-pressure type and a low-pressure one from the perspective of lithofacies balance. There is no plagioclase in the residual minerals of a high-pressure trachyte melt, which is equivalent to eclogite in terms of mineral assemblage. There is no Eu anomaly in such rocks. Low-pressure trachyte is the product of crystallization differentiation of basaltic magma and has an obvious negative Eu anomaly. The δEu values of the Hongshan syenite vary from 0.72 to 1.23, and there is no obvious negative Eu anomaly. It suggests that there may not be a balance between melt and plagioclase in the magma source area of the Hongshan syenite. The magma of the Hongshan syenite was derived from partial melting under high pressure [62]. The FBAS zircons have high $^{176}\text{Hf}/^{177}\text{Hf}$ ratios (0.282176–0.282359), negative $\varepsilon\text{Hf}(t)$ values (−18.3–−11.8) and old two-stage Hf model ages (T_{DM2}) (2.68–3.26 Ga). There are Archean detrital zircons and a few Proterozoic, Paleozoic, and Mesozoic detrital zircons in the FBAS. This shows that the magma may have been derived from the partial melting of the old lower crust of the NCC, and a small amount of upper crustal overburden was incorporated during the process of magma formation and evolution.

Figure 12. (a) The Y versus Sr/Y and (b) the Yb versus La/Yb diagrams [63,64]; (c) The SiO₂ versus Mg# and (d) the SiO₂ versus Ni diagrams [65].

The difference in Rb/Sr ratios among subtypes of the syenite group is significant. The K-rich CAS has a low value of 0.06–0.07 close to that (0.03) of the primitive mantle [49],

whereas Na-rich FBAS has an intermediate value of 0.10–0.11 close to that (0.15) of the continental crust [66]. Both values of CAS and FBAS are lower than the MAS, SP, and BSP (0.13–0.52). The variety in Rb/Sr ratios among these phases is attributed to the introduction of both mantle and crustal materials into the formation of Hongshan syenite magmas, evidenced by Sr-Nd isotopic data of Hongshan syenite. The $(^{87}\text{Sr}/^{86}\text{Sr})_t$ ($t = 135$ Ma) values of the Hongshan syenite are 0.70517–0.70735 [37], and the $\epsilon\text{Nd}(t)$ values are -11.1 – -8.2 . On the $(^{87}\text{Sr}/^{86}\text{Sr})_t$ - $\epsilon\text{Nd}(t)$ diagram (from [37]), most of the sample points from the Hongshan syenite are located on the evolution line of material exchange between the EMI-type mantle and the lower crust.

5.2.2. Petrogenesis of the Diorite and Gabbro

The geological and geochronological characteristics of the diorite and gabbro show that the MD is closely associated with the GD and that they are vein-emplaced syenite. Their mineral compositions and structures are different from that of the other syenites. The rock-forming mineral assemblages of the MD and GD are Pl+Bi+Hb+Or and Pl+Hb, respectively. They are both classified as metaluminous and sodium series rocks. They have the same age of emplacement (124.8 ± 1.3 Ma and 124.1 ± 0.9 Ma) and have similar characteristics of major and trace elements. At the same time, they have almost the same zircon $\epsilon\text{Hf}(t)$ values (-22.3 – -18.4 and -20.0 – -17.0), indicating that they are the products of crystallization differentiation of homologous magma or the partial melting of cognate magma to varying degrees.

Similar to the syenites, the MD from Hongshan have high Sr contents (784–892 ppm), low Yb contents (1.76–1.98 ppm) and high Sr/Y ratios (44.21–49.94). Contrary, the MD has high magnesium contents ($\text{MgO} = 4.04$ – 4.59% , $\text{Mg}^\# = 51.4$ – 54.0), is lower in potassium and sodium ($\text{K}_2\text{O} + \text{Na}_2\text{O} = 7.33$ – 9.41%), and are enriched in ferrophilic elements, such as Cr (35–96 ppm), Co (16.5–23.3 ppm), and Ni (21–53 ppm). In the genetic discrimination diagram of adakitic rocks, the MD samples are located in the adakite area formed by the melting of subducted oceanic plates. Rapp et al. (1999) postulated the concept of “ e = effective basaltic slab melt/mantle peridotite”. When e is greater than 1, basaltic slab melt forms high silicon adakite after metasomatizing mantle peridotite when passing through mantle wedge; When e is less than 1, the partial melting of mantle wedge peridotite occurs, and the melt formed is modified by slab melt to form low silicon adakite. The MD from Hongshan has low SiO_2 (56.10–57.75 wt%) and high TiO_2 (0.70–0.77 wt%), which is similar to the characteristics of low silicon adakite [67]. Therefore, we believe these diorites may originate from the partial melting of mantle wedge peridotite metasomatized by subduction slab melt [68,69].

Mafic magmas can be formed in oceanic ridges, ocean islands, mantle plumes, subducted island arcs, continental margins, and intracontinental deep fault environments [70]. The GD from Hongshan has low SiO_2 (48.94–48.98 wt%) and high MgO (7.84%–8.16 wt%). Additionally, they show the enrichment characteristics of LILEs and LREEs and have REE patterns similar to that of arc magma [71]. The GD is strongly depleted of high field strength elements such as Nb, Ta, and Ti, with a high Th / Nb ratio (0.289–0.292) and low Nb/La ratio (0.273–0.276), which is very similar to typical arc magma (Th/Nb = 0.11–2.0, Nb/La = 0.15–0.63) [72]. On the diagrams of the Zr versus Ti and Ti versus V (Figure 13a,b), the sample points are located in the range of arc magma on the active continental margin.

Figure 13. (a) The Zr versus Ti diagrams [73]; (b) The Ti versus V diagrams [74]. VAB: Volcanic Arc Basalt; WPB: Intra Plate Basalt; VAT: Volcanic Arc Tholeiite; CFB: Continental overflow Basalt; MORB: Mid Ocean Ridge Basalt; OIB: Ocean Island Basalt.

Both the diorite and gabbro in the Handan area have relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ (t) values (0.70581–0.70641, 0.705012–0.705387) and low $\epsilon\text{Nd}(t)$ values (−8.30–16.56, −12.58–13.54) [39,75]. This pattern is obviously different from the geochemical characteristics of typical oceanic crust and asthenospheric mantle, which has depleted Nd isotope compositions ($\epsilon\text{Nd}(t)$ value > 0) and low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. However, this pattern is consistent with the characteristics of mafic rocks formed in the enriched lithospheric mantle source area of the Jiaodong area [32]. It is suggested that the magma associated with the diorite and gabbro in the Handan area may have been derived from the enriched lithospheric mantle. The MD and GD have obviously low $\epsilon\text{Hf}(t)$ values (−22.3–18.4 or −20.0–17.0), and the two-stage model age $T_{\text{DM}2}$ (Hf) (3.6–3.1 Ga) is slightly older than that of the FBAS, indicating that the magma originated from the enriched lithospheric mantle with the characteristics of the middle Archean lower crust.

Experimental petrological studies show that the hydrous minerals phlogopite and amphibole can only exist stably in the lithospheric mantle [76]. Rb and Ba are incompatible elements in phlogopite, while Rb, Sr, and Ba are moderately compatible in amphibole [77]. This means that melts in equilibrium with amphibole should have significantly lower Rb/Sr ratios (<0.1) and higher Ba/Rb ratios (>20) than melts derived from phlogopite-bearing sources, which have extremely low Ba concentrations and Ba/Rb values (<20) [78]. The MD and GD from Hongshan have low Rb/Sr ratios (0.01–0.06) (excluding alkali metasomatic samples) and high Ba/Rb ratios (24.8–29.9), indicating that they may have been derived from magmas generated by the partial melting of an amphibole-bearing region of the enriched lithospheric mantle (Figure 14b). K/Yb and Dy/Yb can constrain the mantle source's composition and degree of partial melting during the generation of mafic rocks, as well as to discriminate between partial melting in the spinel and garnet stability fields of phlogopite-bearing and/or amphibole-bearing lherzolitic mantle [79,80]. Partial melts generated within the spinel stability field generally have low Dy/Yb values (<1.5), whereas partial melting in the garnet stability field produces melts with high Dy/Yb values (>2.5) (Figure 14a). The MD and GD from Hongshan have Dy/Yb ratios ranging from 1.88 to 2.07, plotting between the partial melting curves of garnet-facies amphibole lherzolite and spinel-facies amphibole lherzolite. This implies that partial melting may have taken place in the spinel-garnet transition zone. The large range of K/Yb values suggests variable degrees of partial melting. Robinson and Wood (1998) demonstrated that the minimum pressure at which garnet is stable on the anhydrous solidus of fertile peridotitic mantle is 2.8 GPa, corresponding to a depth of approximately 85 km, with the maximum depth of

the spinel-garnet transition zone being 75–85 km. This indicates that the MD and GD from Hongshan were most likely derived from partial melting of amphibole-bearing lherzolitic lithospheric mantle in the spinel-garnet transition zone at a depth of 75–85 km.

Figure 14. (a) The K/Yb versus Dy/Yb and (b) the Rb/Sr versus Ba/Rb diagrams. Melting curves for garnet lherzolite, spinel lherzolite, garnet-facies phlogopite lherzolite, garnet-facies amphibole lherzolite and spinel-facies amphibole lherzolite are after [79]. (c) (Hf/Sm)_N versus (Ta/La)_N diagram [77]. (d) Nb/Zr versus Th/Zr diagram.

There are two main mechanisms for forming enriched lithospheric mantle endmembers by partial melting: metasomatism of melts or fluids from subducted plates and thermal alteration of volatile-rich (CO₂ + H₂O) from depleted asthenosphere mantle [81,82]. Generally, the fluid-related metasomatism in the subduction process would result in the depletion of Ta and Hf relative to La and Sm, respectively [32]. The depletion of Ta relative to La and enrichment of Hf relative to Sm might be related to the melt-related subduction metasomatism [32]. The low Ta/La ratio and strong depletion in Hf relative to Sm are generally ascribed to the carbonatite metasomatism [83]. The MD and GD from Hongshan have low (Ta/La)_N ratios (0.28–0.35) and (Hf/Sm)_N ratios (0.60–1.20). In the diagram of (Ta/La)_N–(Hf/Sm)_N, the samples fall in the subduction-related fluids metasomatism (Figure 14c), indicating that the cause of metasomatism may be a fluid-related process. In addition, the diagram of Th/Zr–Nb/Zr also shows the characteristics of enriched mantle modification by subducted slab-derived fluids (Figure 14d).

The above discussion indicates that the MD and GD from Hongshan most likely originated from enriched lithospheric mantle metasomatized by slab-derived hydrous fluids. The Hongshan syenite may be originated from mixing the thickened lower crust and the enriched lithospheric mantle magma.

5.3. Geodynamic Implications

During the Early Cretaceous, mafic magmatism was widely developed in the eastern and central parts of the NCC (including Jiaodong, Liaodong, Luxi, Taihang Mountains, and Dabie Sulu areas) [20,32,84–86]. Accompanied by large-scale magmatic activities, the NCC also developed massive gold mineralization, a large number of metamorphic core complexes, and fault basins [9,87]. These strong magmatic, tectonic, and metallogenic events indicate that the NCC was in an extensional tectonic regime and lost its stability during the early Cretaceous [88].

At present, several models have been proposed to interpret the destruction process of the NCC, including delamination [2] and thermal erosion [89], which are the most widely accepted. The age and genesis of the Hongshan complex may provide some clues for understanding crust-mantle interaction and destruction mechanism, the central part of the NCC. Ma et al. (2016) explained the co-occurrence of the Early Cretaceous asthenospheric and lithospheric mantle-derived mafic rocks in the Jiaodong Peninsula by using the delamination model and considered that the Jiaodong Peninsula and the Bohai Sea were the centers of the lithospheric destruction process of NCC. The rapid and intense lithospheric delamination would trigger thermomechanical erosion within the interior domains of the NCC, such as the Taihang Mountains [86]. The geochemical characteristics of the Hongshan complex indicate that magmas have experienced two processes: partial melting of enriched lithospheric mantle and subsequent mixing with thickened lower crust. In the delamination model, melts of the delaminated lower crust will inevitably interact with the mantle peridotite while migrating upward, resulting in elevated MgO, Cr, and Ni concentrations [2,90]. As mentioned above, the low MgO contents and depleted in Cr, Co, and Ni of Hongshan syenites indicate that it originated from partial melting of the thickened lower crust caused by thermal erosion. It is generally accepted that the destruction of the NCC in the Early Cretaceous was related to the subduction of the Paleo-Pacific plate [2,8,10]. Some studies suggest that the subduction of the Paleo-Pacific plate did not affect the central part of the NCC because of too far away from the coastline, more than 1000 km. However, recent geophysical data show that horizontal subduction of the Paleo-Pacific plate is trapped in the mantle transition zone under the craton [54,91]. The influence of horizontal plate subduction can be as far as 2000 km. Suppose the huge extension of eastern China since Mesozoic and the distance of Japan Sea formed in Cenozoic are removed. In that case, the distance between Taihang Mountain and the ancient Pacific subduction zone should be less than 2000 km [37,92]. The MD and GD in Hongshan are the products of partial melting of lithospheric mantle metasomatized by subducted slab fluid, which corresponds to the subduction of the Paleo-Pacific plate in the central NCC.

Combining the geological, geochronological, geochemical, and isotopic features, we propose a model to interpret the petrogenesis of the Hongshan complex (Figure 15). Along with the subduction of the Paleo-Pacific plate to the east of Eurasia in the Late Triassic [93], the slab-released fluid modified the overlying mantle. It transformed the Paleozoic cratonic lithospheric mantle to Mesozoic enriched lithospheric mantle. In the Early Cretaceous, the roll-back of the Paleo-Pacific plate led to an extremely extensional environment in the NCC. The enriched lithospheric mantle was heated by upwelling asthenosphere and then partial melting to form the widespread mafic magma chamber in the NCC at a depth of 75–80 km. The magmatic emplacement process resulted in partial melting of the overlying thickened lower crust. Finally, the mixed magma emplaced and formed Hongshan syenite.

Figure 15. Tectonic model for the generation and emplacement of the Hongshan complex in the southern Taihang Mountains (modified after [87]).

6. Conclusions

The Hongshan rocks are mainly composed of syenite (including the FBAS, MAS, CAS, SP, and BSP), diorite (the MD), and gabbro (the GD). Zircon U-Pb chronology shows that the syenite and the diorite-gabbro emplacements occurred at ~130 Ma and ~125 Ma, respectively. Field geology, petrology, and element geochemistry demonstrate that the parental magmas of Hongshan syenite originated from the mixture of partially melted thickened lower crust and partially melted lithospheric mantle. The Hongshan diorite and gabbro magma most likely originated from enriched lithospheric mantle metasomatized

by slab-derived hydrous fluids. They all formed in an extensional environment associated with the subduction and roll-back of the Paleo-Pacific plate beneath the North China plate in the Early Cretaceous.

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