

The Jiashan Syenite in northern Hebei: A record of lithospheric thinning in the Yanshan Intracontinental Orogenic Belt

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Abstract

The Early Cretaceous Jiashan Syenite is located in a region of late Jurassic crustal thickening. The Jiashan Syenite can be divided into three concentrically arranged units, the Jiangjiawan, Longtangou and Longtannangou units, which were intruded sequentially. Geochemically, the Jiashan Syenite has a high Ga/Al ratio (>3), is enriched in silica, alkalis, Fe, REE, Th, Ga, Nb, Zr and Hf, is depleted in Mg, Ba, Sr and Ti and in transition elements such as Cr, Co, Ni and V. The three units of the Jiashan Syenite have Ce/Pb ratios ranging from 6.12 to 13.41 and are enriched in light REE (LREE) with a moderate Eu negative anomaly. The $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios range from 0.701409 to 0.707405, with a mean of 0.70379. The $\epsilon_{\text{Nd}}(t)$ values of -2.27 to -5.58 indicate that the magma was probably derived from enriched mantle. The Jiashan Syenite is a post-orogenic intrusion, and can be considered to be an A-type granite. It was emplaced in an environment of lithospheric extension during asthenospheric mantle upwelling. This suggests that the regional compressional shortening and crustal thickening tectonic regime in the Yanshan Orogenic Belt during the Late Jurassic (ca. 135 Ma) changed to lithospheric extension and thinning in the Early Cretaceous.

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1. Introduction

The Yanshan Intracontinental Orogenic Belt is located on the northern margin of the North China Plate and is the eastern part of the greater Yinshan Orogenic Belt, which extends westward ~ 1100 km from north Bohai Bay to the Baotou in Inner Mongolia, where it becomes concealed beneath the sands and gravels of the Gobi Desert along the Mongolian-Chinese border (Davis et al., 2001). The intra-plate Jurassic–Cretaceous Yanshan Belt experienced fold-

ing, contractional and extensional faulting, and contemporaneous terrestrial sedimentation and magmatism (Davis et al., 1998). The tectonics of the Yanshan Orogenic Belt has been the focus of intensive study in recent years (Zhao, 1990; Bai et al., 1991, 1999; Mao and Yan, 1992; Deng et al., 1996, 2000; Liu and Shi, 1998; Yan et al., 1998; Shao et al., 1999, 2001; Xu et al., 1999; Zhu et al., 1999; Davis et al., 2001; Li et al., 2001a,b; Zhang et al., 2001a; Qian et al., 2002). Some recent authors propose that the E- to ENE-trending deformation of the Yanshan Belt, involving Archean basement rocks in contractional faulting, indicates a ‘thick-skinned’ tectonic style, with thrust faults steepening downwards into the basement (Bureau of Geology and Mineral Resources of Hebei Province, 1989; Zhang et al., 1996; Chen, 1998). However, near Chengde

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County in northern Hebei Province Davis et al. (1998, 2001) discovered synformally folded and thin-skinned thrust faults with large displacements.

Mesozoic magmatism and the corresponding tectonic regime in the Yanshan Belt is very complex and has attracted the attention of many geologists. Ren et al. (1980) and Cheng (1994) believed that the Yanshan Belt was a part of the Pacific active continental margin, which was formed by the interaction of the Pacific Plate with the Asia continent, and that magmatic activity occurred in a compressional tectonic setting. Yoshio et al. (1994) and Zhao et al. (1998) propose that magmatic activity was the result of low-angle subduction of the Pacific Plate. Deng et al. (1996) considered that it was due to island-arc volcanic activity formed by the convergence between the North China Craton and the Izanagi oceanic lithosphere. Most geologists (Xu, 1990; Zhao et al., 1994; Zheng et al., 2000; Zhu et al., 1999) think that the formation of the Yanshan tectonomagmatic belt is closely associated with interaction of the Pacific Plate and Eurasian Plate. Davis et al. (1998, 2001), on the other hand, propose that the collision of the Siberian and North China Plates upon closure of a Jurassic and Early Cretaceous Mongolo-Okhotsk Ocean, more than 800–1100 km to the north, may have been responsible for Yanshan north–south compression.

The Yanshan Belt was later overprinted by a magmatic regime related to the westward subduction of the Pacific Plate beneath the North China Plate. Furthermore, Fan and Guo (2005) suggested a new tectonic model, which emphasized that the Yanshan Belt was affected by the interaction of several tectonic plates, including the paleo-Pacific Plate, the Siberian Plate, the Tethyan tectonic domain and the Indo-China Block. These interactions triggered lithospheric extension, asthenospheric upwelling and decompressional melting of enriched mantle sources, and the extensive emplacement of Late Mesozoic magmas. In contrast, Shao et al. (2001), Li et al. (2001a) and Zhang et al. (2001a) suggest that the formation and evolution of Mesozoic magmas was related to underplating by intraplate basaltic magma and was not related to subduction of the Pacific Plate.

Although in previous studies Huang et al. (1977), Ren et al. (1980) and Davis et al. (1998) have suggested that compressional shortening and crustal thickening occurred during Jurassic time in the Yanshan area, during the Cretaceous lithospheric extension and crustal thinning became dominant. When did the tectonic regime change from N–S compression to E–W extension? What is the evidence provided by magmatic activity during this change? These questions are of great interest to the geological community and studies of igneous systems that are associated with lithospheric extension may be important to cast light on these issues.

The Jiashan Syenitic Pluton is close to the Late Jurassic Chengde Thrust Fault, which has a displacement of at least 40–45 km (Zheng et al., 2000; Davis et al., 2001). The Jiashan Syenite with a composition similar to A-type granites

was emplaced in a late-orogenic lithospheric extensional environment. It provides an early geological record of lithospheric thinning in the Yanshan Intracontinental Orogenic Belt. Therefore, the study of the Jiashan Syenite Pluton can provide important clues for understanding regional extension and lithospheric thinning processes. Based on detailed field surveys and systematic sampling, combined with petrographic, mineralogical and geochemical studies. In this paper we present the geology and geochemistry of the Jiashan Syenite intrusion and discuss the implications for Early Cretaceous regional lithospheric thinning, post-orogenic extension and the emplacement of A-type granitoids.

2. Geological setting

The Yanshan Belt is an extensive region in eastern Asia on the northern margin of the North China Craton, underlain by 3.8–2.5 Ga Archean basement rocks (Liu et al., 1992). The Archean basement is composed of gneiss, granulite and quartzite and is overlain by a Middle–Late Proterozoic (ca. 1850–800 Ma) shallow-water marine succession with a thickness of up to 10 km. The Phanerozoic rocks in the region comprise Cambrian–Middle Ordovician shallow-marine carbonates; Upper Carboniferous–Lower Permian carbonates and coal-bearing clastics, Upper Permian–Triassic red beds and conglomerates. Jurassic coal-bearing clastics and continental volcano-sedimentary units overlie older units unconformably (Davis et al., 2001). The Cretaceous consists of terrestrial volcanic rocks, volcanoclastic and clastic rocks.

Magmatic activity in the Yanshan Orogenic Belt began ca. 195–185 Ma (Early Jurassic; Bureau of Geology and Mineral Resources of Hebei Province, 1989; Xu, 1990), with most of the granitic plutons being Cretaceous in age (ca. 138–113 Ma, Davis et al., 2001). A few plutons are Late Jurassic and Jurassic–Cretaceous in age (ca. 159–141 Ma, Bureau of Geology and Mineral Resources of Hebei Province, 1989; Xu, 1990; Davis et al., 2001). Mesozoic terrestrial sedimentation, magmatism and deformation, including multiple phases of folding, and strike-slip faulting, characterize the Yanshan fold-and-thrust belt (Davis et al., 2001). The studies by Davis et al. (2001) indicate that Late Jurassic and Early Cretaceous compressional deformation in the Yanshan Belt was much more intense than is generally believed. Five orogenic episodes in the Yanshan Belt are recognised (Deng et al., 2004): 1. Pre- and initial orogenic (Early Jurassic); 2. Early orogenic (Middle Jurassic); 3. Peak orogenic (Late Jurassic); 4. Late orogenic (early Early Cretaceous); and 5. Post-orogenic.

Jurassic tectonic deformation formed the framework for the E–W-trending Yanshan Fold-Thrust Belt (Zhao et al., 2004). Late Jurassic–Early Cretaceous intermediate-felsic volcanic rocks and intrusive rocks have geochemical features typical of adakite in the Yanshan-Liaoning area (Li et al., 2001a; Zhang et al., 2001a,b). Jurassic thrust tectonics and molasse sedimentation are widespread, indi-

cating that the compressive deformation and crustal thickening dominated throughout the Yanshan area during the Late Jurassic (He et al., 1998; Davis et al., 2001; Yang et al., 2001; Zhang et al., 2002; Zhao et al., 2002; Li and Li, 2004).

3. Geology of the Jiashan Syenite

The Jiashan Syenite is located in the eastern segment of the Yanshan Intracontinental Orogenic Belt. Middle–Late Jurassic strata are well developed in this area (Fig. 1),

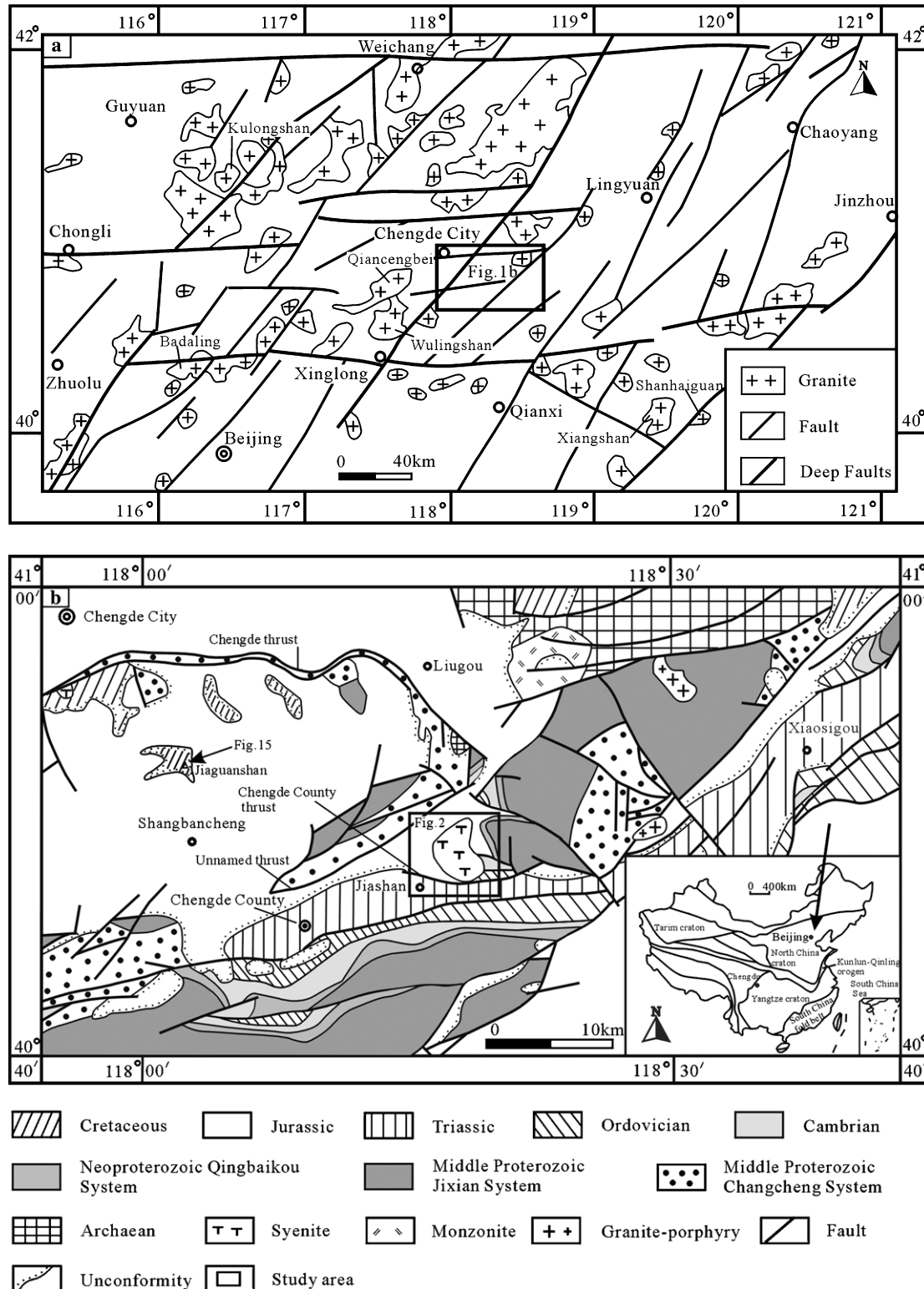


Fig. 1. (a) Simplified geological map showing the distribution of Mesozoic granites in the Yanshan area (after Zhu et al., 1999); (b) Regional geological map of Jiashan (after Bureau of Geology and Mineral Resources of Hebei Province, 1989).

consisting of lavas, volcanoclastic rocks and coal-bearing clastic rocks. Li and Li (2004) studied the Middle–Late Jurassic of the Tiaojishan Formation in the Chengde County, and reported that trachyandesite and trachyte have the geochemical features of adakite. The trachyandesite is a product of magmas derived from partial melting of lower continental calc-alkaline basaltic crust. The Early Cretaceous strata in the area comprise an andesite–trachyandesite–trachyte association, which belongs to the calc-alkaline to alkaline series (Zhu et al., 1999). In the Early Cretaceous, terrestrial volcanic eruptions and extensive coeval emplacement of intrusive rocks took place. They consist predominantly of felsic (e.g., Shidongzigou granite porphyry) and alkalic rocks. The rock association is diorite porphyry, granite porphyry and syenite.

The Jiashan Pluton is situated near Jiashan Town, Chengde County, Hebei Province. Tectonically, the Jiashan Pluton is located at the southern side of the regional Pingquan–Gubeikou Thrust (Zhao, 1990) and immediately adjacent to the ‘unnamed thrust’ of Davis et al. (1998). On the southern side of the Jiashan Pluton lies the Xiabancheng Basin, in which Triassic through Upper Jurassic strata, intensely folded in the Late Jurassic, are well developed. On the western side, the Jiashan Pluton is close to the Chengde Thrust Sheet (Davis et al., 1998), which has a displacement of at least 40–45 km (Zheng et al., 2000; Davis et al., 2001). The Chengde Thrust is Late Jurassic in age (161–132 Ma).

The Jiashan Pluton is exposed over an area 5 km long from south to north, with a maximum width of 3.8 km. It is elliptical in shape, with its long axis trending N–S and exposed over an area of approximate 14 km² (Fig. 2). The Jiashan Pluton intruded coal-bearing clastic rocks of the Early Jurassic Xiahuayuan Formation, which are the youngest strata in this area (Sun et al., 1996; Yang et al., 1999), and is intruded into the Chengde County thrust fault (N.B. This is not the Chengde Thrust mentioned above). The whole-rock K–Ar date reported by Yang and Li (1997) suggests emplacement of the pluton at 94.9 ± 2.3 Ma, but the U–Pb zircon date indicates a cooling age and crystallization at 113 ± 2 Ma (Zheng et al., 2000; Davis et al., 2001), implying that the Jiashan pluton was emplaced in the Early Cretaceous. Contact thermal metamorphism is developed in the surrounding country rocks. The exocontact zones are characterized by andalusite-bearing quartzofeldspathic hornfels and andalusite quartzofeldspathic hornfels, with zoning from east to west. Silicification is also irregularly developed in some localities. A chilled zone in the syenite forms the endocontact. There is a regular and clear contact boundary between the pluton and the country rocks, and the plane of contact is straight and dips outward towards the country rocks. On the basis of field evidence and petrographic analysis, the Jiashan Pluton can be divided into three concentric ring-shaped zones (Fig. 2), together forming a cogenetic magmatic intrusive series. From early to late, the three units forming the ring-shaped zones are: the Jiangjiawan, Longtangou and Longtannangou units. The Jiangjiawan Unit forms the outer ring of the Jiashan Pluton; the Longtannangou Unit forms the core of the pluton, and the

Longtangou Unit occurs between these two units, and has the largest area of exposure. There is no sharp intrusive contact between the Longtangou and Jiangjiawan units. Field evidence indicates that the units become younger toward the center of the pluton. A similar case is recorded for the Tuolumne Intrusive Suite in California (Coleman et al., 2004).

4. Petrology

4.1. Jiangjiawan unit (KJ)

The Jiangjiawan unit consists of coarse- to medium-grained, amphibole–pyroxene syenite. The rock has a coarse- to medium-grained, subhedral granular texture. The principal minerals are K-feldspar (70–80%), amphibole (5–10%), clinopyroxene (5–10%), plagioclase (5%) and quartz (<5%). K-feldspar is generally subhedral–anhedral granular, 2–5 mm, long but in a few cases 5–7 mm. The clinopyroxene is subhedral prismatic, ranging in size from 0.1 to 2.7 mm. The accessory minerals are magnetite, zircon, apatite, ilmenite and pyrite.

4.2. Longtangou unit (KL)

The unit appears as coarse-grained amphibole–quartz syenite. The rock has a coarse-grained subhedral granular texture and a massive structure. The principal minerals are K-feldspar (62–85%), amphibole (5–10%), clinopyroxene (4–6%), plagioclase (2–5%) and quartz (5–8%). The K-feldspar is subhedral to granular, 5–8 mm long in general and in a few cases 2–5 mm. The amphibole is prismatic euhedral, 0.5–2 mm long. The accessory minerals are mainly magnetite, zircon, apatite and pyrite, with minor ilmenite and xenotime.

4.3. Longtannangou unit (KLn)

This unit is a massive porphyritic amphibole–quartz syenite. The phenocrysts (30%) include K-feldspar (2.5–15 mm long) and small amounts of plagioclase and clinopyroxene. The groundmass shows a fine-grained subhedral granular texture and is composed of K-feldspar (45–50%), amphibole (5–10%), quartz (5–7%), clinopyroxene (3–5%), plagioclase (5%) and minor biotite. The accessory minerals are magnetite, apatite, zircon, pyrite, ilmenite with lesser titanite, xenotime and molybdenite.

Quartz monzodiorite cognate enclaves are observed in the Longtannangou Unit. Most enclaves have rounded or elliptical shapes and a few show rectangular and irregular shapes. The enclaves generally range in diameter from 1 to 3 cm and in a few cases from 7 to 30 cm, have a porphyritic texture and a massive structure. The phenocrysts consist of orthoclase (5–10%) and minor clinopyroxene. The groundmass shows a fine-grained texture and is composed of plagioclase (45–50%), K-feldspar (10–15%), quartz (10–15%), clinopyroxene (10–15%) and amphibole (5–10%). The accessory minerals are magnetite, apatite and zircon.

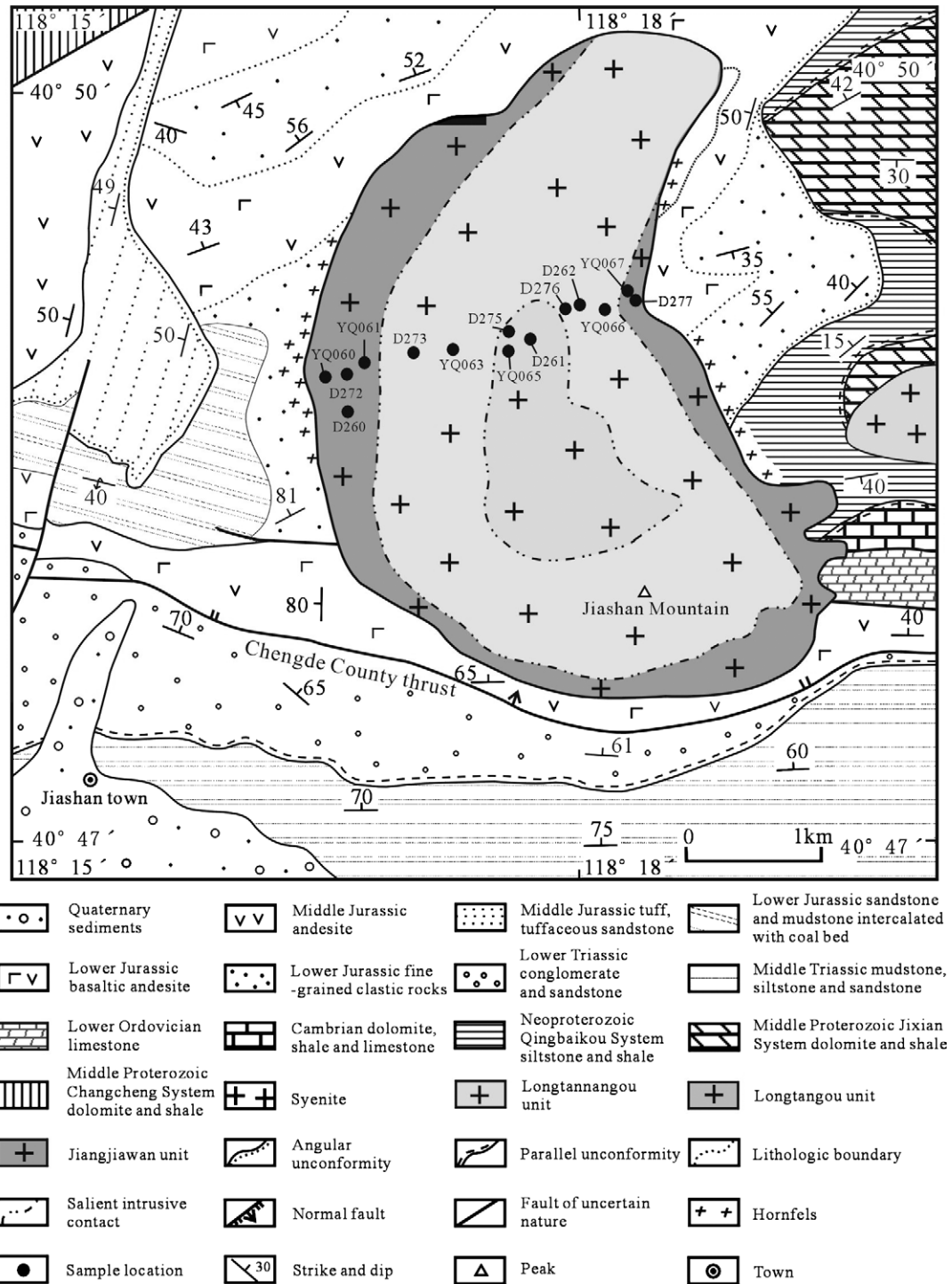


Fig. 2. Geological map of the Jiashan Syenite Pluton, Chengde (after the 1:50,000 Shanggu station regional geological map).

5. Mineral chemistry

Chemical analyses of representative minerals were carried out at the Institute of Mineral Resources, Chinese Academy of Geological Sciences, using the JXA8800R electron microprobe at an accelerating voltage of 20 kV and currents of 2×10^{-8} A.

Analytical results from 22 alkali feldspars and one plagioclase are listed in Table 1. The alkali feldspars show wide

end-member compositional variations, with Or=17.2–76.5%, Ab=22.9–79.5% and An=0.6–7.9% (Fig. 3). The plagioclase in the groundmass is oligoclase with An=12.2, Ab=83.0, and Or=4.8.

Results of representative analyses of amphiboles from the Jiashan Syenite are listed in Table 2. According to the classification defined by Leake et al. (1997), the amphiboles of the Jiashan Pluton are ferro-edenite with minor ferrohornblende and ferro-actinolite (Fig. 4). Microprobe

Table 1
Electron microprobe analyses of alkali-feldspar and plagioclase from Jiashan Syenite, Chengde

Unit	KJ						KL					KLn											
Sample	D260			D277			D262		D273			D261						D275					
Dot. No.	1	2	3	1	2	3	1	2	1	2	3	1£ª	2£ª£ª	3£ª£ª	4£ª£ª	5£ª	6£ª	1£ª£ª	2£ª£ª	3£ª£ª	4£ª	5£ª	6£ª
SiO ₂	65.99	66.84	65.80	64.85	67.78	65.65	66.24	66.97	65.81	66.43	66.01	65.25	64.47	65.08	65.55	65.00	65.49	67.22	65.45	65.57	67.23	66.23	65.34
TiO ₂	0.00	0.00	0.08	0.00	0.00	0.14	0.07	0.06	0.18	0.02	0.05	0.07	0.06	0.00	0.07	0.00	0.02	0.00	0.03	0.03	0.00	0.09	0.00
Al ₂ O ₃	18.84	19.44	18.71	18.83	19.60	20.22	19.62	20.82	19.39	19.28	19.24	19.41	18.24	18.73	18.84	18.35	18.42	19.62	18.80	19.07	19.80	19.50	18.78
FeO	0.25	0.02	0.15	0.17	0.35	0.16	0.16	0.24	0.14	0.03	0.22	0.24	0.34	0.08	0.28	0.07	0.13	0.45	0.16	0.35	0.25	0.19	0.25
MnO	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.06	0.05	0.00	0.14	0.00	0.02	0.00	0.10	0.01	0.00	0.02	0.06	0.02	0.00
MgO	0.00	0.19	0.03	0.03	0.07	0.03	0.07	0.10	0.06	0.05	0.08	0.02	0.00	0.04	0.08	0.03	0.07	0.22	0.08	0.05	0.05	0.17	0.08
CaO	0.43	0.91	0.24	0.75	0.85	1.50	0.92	2.20	0.87	0.66	0.35	0.85	0.15	0.07	0.45	0.08	0.24	0.51	0.34	0.61	1.05	0.25	0.66
Na ₂ O	6.09	8.92	5.88	4.59	8.62	6.41	6.13	8.76	6.04	5.52	5.93	4.69	3.44	3.51	5.54	2.97	3.76	8.83	5.29	4.38	8.13	7.18	5.23
K ₂ O	7.47	2.82	7.67	9.32	2.97	5.53	6.50	0.73	7.10	8.49	7.58	9.61	11.99	12.06	8.39	12.78	10.85	2.82	8.28	9.25	2.74	4.87	7.44
Cr ₂ O ₃	0.00	0.09	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	
NiO	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Total	99.07	99.41	98.56	98.54	100.24	99.71	99.71	100.00	99.59	100.54	99.51	100.14	98.83	99.57	99.22	99.28	99.08	99.68	98.43	99.33	99.31	99.67	97.78
Si	2.994	2.977	3.004	2.980	3.007	2.960	2.989	2.980	2.972	2.977	2.984	2.948	2.970	2.970	2.977	2.985	3.007	2.992	3.000	2.997	3.021	2.977	3.021
Ti	0.000	0.000	0.003	0.000	0.000	0.005	0.002	0.002	0.006	0.001	0.002	0.002	0.002	0.000	0.002	0.000	0.001	0.000	0.001	0.001	0.000	0.003	0.000
Al	1.007	1.020	1.007	1.020	1.025	1.074	1.043	1.092	1.032	1.018	1.025	1.034	0.990	1.008	1.008	0.993	0.997	1.029	1.016	1.027	1.048	1.033	1.023
Fe	0.009	0.001	0.006	0.007	0.013	0.006	0.006	0.009	0.005	0.001	0.008	0.009	0.013	0.003	0.011	0.003	0.005	0.017	0.006	0.013	0.009	0.007	0.010
Mn	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.002	0.002	0.000	0.005	0.000	0.001	0.000	0.004	0.000	0.000	0.001	0.002	0.001	0.000
Mg	0.000	0.025	0.002	0.002	0.005	0.002	0.005	0.015	0.004	0.003	0.005	0.001	0.000	0.003	0.005	0.002	0.005	0.015	0.005	0.003	0.003	0.011	0.006
Ca	0.021	0.043	0.012	0.037	0.040	0.072	0.044	0.105	0.042	0.032	0.017	0.041	0.007	0.003	0.022	0.004	0.012	0.024	0.017	0.030	0.051	0.060	0.033
Na	0.536	0.770	0.520	0.409	0.742	0.560	0.536	0.756	0.529	0.480	0.520	0.411	0.307	0.311	0.488	0.264	0.335	0.762	0.470	0.388	0.708	0.626	0.469
K	0.432	0.160	0.447	0.546	0.168	0.318	0.374	0.041	0.409	0.485	0.437	0.554	0.705	0.702	0.486	0.749	0.636	0.160	0.484	0.539	0.157	0.279	0.439
Cr	0.000	0.030	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.000
End members																							
Ab	52.7	78.1	52.7	40.0	77.0	57.5	54.7	83.0	52.5	46.9	51.9	38.8	26.3	26.7	47.7	22.9	32.7	79.5	46.9	39.1	76.3	63.4	48.4
An	2.1	4.7	1.2	3.3	4.5	7.9	4.8	12.2	4.4	2.8	1.8	3.6	1.1	0.6	1.8	0.6	1.3	2.7	1.8	3.2	5.7	6.5	3.5
Or	45.2	17.2	47.1	57.7	18.5	34.6	40.5	4.8	43.1	50.3	46.3	57.6	72.6	72.7	50.5	76.5	66.0	17.8	51.3	57.5	18.0	30.1	48.1
Mineral	(1)	(2)	(1)	(1)	(2)	(2)	(2)	(4)	(1)	(1)	(1)	(1)	(3)	(3)	(1)	(3)	(1)	(2)	(1)	(1)	(2)	(2)	(1)

Note. Analyzed by Zhou Jianxiong. FeO, total iron; £^a, phenocryst; £^a£^a, groundmass. (1) Na-orthoclase; (2) anorthoclase; (3) orthoclase; (4) oligoclase.

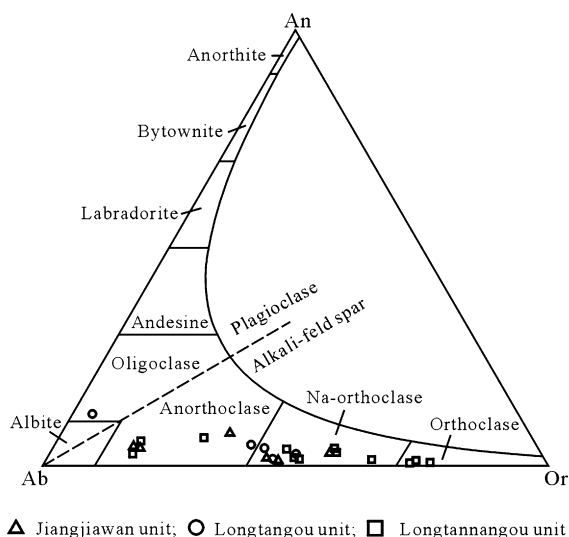


Fig. 3. Representative elemental analysis of feldspars for the Jiashan Syenite, Chengde.

analysis gave the following composition (%) of ferro-edeneite: $\text{Al}_2\text{O}_3 = 3.87\text{--}7.02$, $\text{FeO} + \text{Fe}_2\text{O}_3 = 24.57\text{--}31.24$, $\text{MgO} = 2.01\text{--}6.32$, $\text{CaO} = 9.30\text{--}11.10$ and $\text{Na}_2\text{O} = 1.73\text{--}2.24$.

Analytical results of clinopyroxene from the Jiashan Syenite are listed in Table 3. The clinopyroxene of the Jiashan Syenite includes hedenbergite and augite (Fig. 5). The composition of hedenbergite has a narrow range, with the end members ranging from $\text{Wo}_{45.95\text{--}47.27}$ $\text{En}_{11.39\text{--}18.01}$ $\text{Fs}_{35.15\text{--}42.50}$. The end members of augite range widely, with $\text{Wo}_{27.67\text{--}44.43}$, $\text{En}_{5.82\text{--}23.77}$ $\text{Fs}_{33.56\text{--}66.32}$. The clinopyroxene of the Jiangjiawan Unit is mainly hedenbergite, with minor augite. Clinopyroxene from the Longtangou Unit is mainly augite, while hedenbergite is less abundant; the clinopyroxene from the Longtannangou Unit is hedenbergite and augite.

6. Whole-rock geochemistry

6.1. Samples and analytical methods

The samples studied in this paper were collected from a section across the three units of the Jiashan Pluton (Fig. 2). Eight fresh and representative samples were selected for geochemical analyses by thin-section optical microscopy. The rocks were split into slabs by the contamination-free method, and the central portions were handpicked and powdered using an agate mill at the Institute of Geophysical and Geochemical Exploration, Chinese Academy of Geological Sciences. The whole-rock abundances of the major elements, rare earth elements (REE) and trace elements were determined in the Institute of Geophysical and Geochemical Exploration, Chinese Academy of Geological Sciences. FeO was analyzed by the volumetric method; CO_2 and C_{org} analyzed by the conductometric titration method; H_2O^+ analyzed by the gravimetric method. The other major elements were analyzed using X-ray fluorescence spectrometry (XRF). The REE were determined by using an inductively coupled plasma mass spectrometer (ICP-MS) and the

trace elements were analyzed with ICP-MS and X-ray fluorescence spectrometry (XRF). The international standards GSR1, GRS2 and GRS5 were used for monitoring during the analytical process and some samples were repeatedly measured.

Sm, Nd, Rb and Sr isotopes were determined at the Institute of Geology, Chinese Academy of Geological Sciences. Each sample from whole-rock powder was about 500 mg in weight (<200 mesh), which was loaded in low-pressure air-proof dissolving sample cup and $\text{HF} + \text{HNO}_3$ was added to dissolve the sample. When the sample was dissolved completely, the sample was evaporated to dry and then was dissolved in HCl. The sample was divided into two parts: one part was used to determine the content, and the other part was used to determine the Nd and Sr ratio. The isotope contents were analyzed by the isotope dilution method. The diluent material was put into the sample and they were mixed and dissolved in HClO_4 , and translated into HCl medium. The MREE, Rb and Sr were separated on the cation exchange column ($\text{AG500W} \times 8(\text{H}^+)$, 200–400 mesh). The Rb and Sr contents were determined with a MAT-261 mass spectrometer.

The Nd and Sr isotope analytical procedure is as follows: The HClO_4 was added to the sample and the sample was evaporated to dry. The REE and Sr were separated on the cation exchange column, and Nd was separated from Sm with the HDEHP exchange column. The Sr and Nd isotopic ratios were determined using the mass spectrometer. The measured $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were normalized by $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ and $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$, respectively, and an isotopic mass fractionation correction was made following Rayleigh's law. The blank levels of Sm and Nd were 5×10^{-11} g, and the blanking level of Rb and Sr was $10^{-9}\text{--}10^{-10}$ g. The $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of the J.M. Nd_2O_3 standard and GBW04419 standard measured during this study were 0.511125 ± 8 (2σ) and 0.512725 ± 10 (2σ), respectively. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the NBS987SrCO₃ standard measured during this study was 0.71025 ± 2 (2σ). Calculated parameters: $\lambda_{\text{Rb}} = 1.41 \times 10^{-11}/\text{a}$, $\lambda_{\text{Sm}} = 6.54 \times 10^{-12}/\text{a}$, $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{UR}} = 0.512638$ and $(^{147}\text{Sm}/^{144}\text{Nd})_{\text{UR}} = 0.1967$.

6.2. Major elements

The major element data of representative samples from the three ring-shaped units of the Jiashan Syenite intrusion are listed in Table 4. The compositions of the rocks are different in the three units. The SiO_2 concentration of the Jiangjiawan Unit ranges from 61.34% to 63.15% with a mean of 62.47%; $\text{K}_2\text{O} + \text{Na}_2\text{O} = 10.44\text{--}11.56\%$ with a mean of 11.03%. For the Longtangou Unit, SiO_2 contents vary from 63.62% to 66.46%, $\text{K}_2\text{O} + \text{Na}_2\text{O}$ ranges from 10.26% to 11.15% with a mean of 10.60%. The Longtannangou Unit has higher SiO_2 (64.77–65.85%) with a mean of 65.48%, $\text{K}_2\text{O} + \text{Na}_2\text{O} = 9.95\text{--}10.5\%$, $\text{Na}_2\text{O}/\text{K}_2\text{O} = 0.81\text{--}1.04$ (in most cases 0.92–0.99). There is a negative correlation between SiO_2 contents and MgO, TiO₂, CaO, Na₂O and

Table 2
Electron microprobe analyses and atomic proportions of the representative amphibole from Jiashan Syenite, Chengde

Unit	KJ						KLn						KL					
Sample	D260			D277			D261			D275			D262			D273		
Dot. No.	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
SiO ₂	44.44	44.22	45.21	44.43	44.19	43.21	43.78	43.46	43.28	42.82	44.16	43.01	42.29	42.50	41.90	46.92	42.03	45.75
TiO ₂	1.15	1.17	1.14	1.25	0.96	1.63	1.00	1.42	1.43	1.47	1.20	1.18	1.45	1.26	1.49	0.75	1.46	1.16
Al ₂ O ₃	3.97	4.08	3.87	4.76	4.79	5.52	5.95	6.16	7.02	5.64	5.73	5.73	6.28	5.98	6.25	2.96	5.93	3.85
FeO	30.24	30.47	29.34	29.98	31.24	27.94	24.57	27.24	25.18	28.96	28.07	28.68	29.32	29.76	30.02	30.19	30.43	30.92
MnO	0.59	0.75	0.54	0.81	0.89	0.66	0.78	0.76	0.72	0.76	0.49	0.63	0.65	0.63	0.63	0.91	0.55	0.74
MgO	3.41	3.16	3.52	2.88	2.01	3.69	6.32	4.53	5.20	3.22	4.03	3.26	2.62	2.95	2.45	2.87	2.33	3.03
CaO	9.61	9.60	9.30	10.31	10.33	10.58	11.10	10.83	10.89	10.60	11.10	10.63	10.82	10.84	10.72	10.84	10.56	9.54
Na ₂ O	1.82	2.13	2.23	1.93	1.84	1.73	1.88	2.24	1.86	1.93	1.94	1.82	2.11	1.75	1.99	0.94	1.86	2.27
K ₂ O	1.06	1.03	1.03	1.00	0.81	1.33	1.07	1.20	1.21	1.16	1.15	1.20	1.29	1.46	1.28	0.71	1.23	0.91
Cr ₂ O ₃	0.06	0.02	0.06	0.24	0.13	0.45	0.00	0.05	0.00	0.00	0.22	0.00	0.06	0.05	0.21	0.01	1.24	0.10
NiO	0.00	0.00	0.00	0.00	0.05	0.04	0.00	0.00	0.02	0.00	0.05	0.07	0.08	0.10	0.09	0.07	0.06	0.05
Total	96.35	96.63	96.24	97.59	97.24	96.78	96.45	97.89	96.81	96.56	98.14	96.21	96.97	97.28	97.03	97.17	97.68	98.32
<i>Number of cations per 23 oxygens</i>																		
Tsi	7.141	7.119	7.264	7.112	7.133	6.959	6.926	6.890	6.858	6.938	7.011	6.978	6.889	6.876	6.823	7.505	6.789	7.232
Tal	0.751	0.774	0.732	0.888	0.867	1.041	1.074	1.110	1.142	1.062	0.989	1.013	1.111	1.124	1.177	0.495	1.128	0.717
Tfe3	0.108	0.107	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.083	0.051
Sum_T	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Cal	0.000	0.000	0.000	0.009	0.044	0.006	0.035	0.040	0.168	0.014	0.082	0.083	0.094	0.016	0.021	0.062	0.000	0.000
CCr	0.008	0.003	0.008	0.030	0.017	0.057	0.000	0.006	0.000	0.000	0.028	0.000	0.008	0.006	0.027	0.001	0.158	0.012
Cfe3	0.480	0.407	0.346	0.209	0.257	0.118	0.245	0.114	0.120	0.162	0.000	0.119	0.000	0.186	0.130	0.099	0.206	0.369
Cti	0.139	0.142	0.138	0.151	0.117	0.197	0.119	0.169	0.170	0.179	0.143	0.144	0.178	0.153	0.182	0.090	0.177	0.138
CMg	0.817	0.758	0.843	0.687	0.484	0.886	1.491	1.071	1.228	0.778	0.954	0.789	0.636	0.712	0.595	0.684	0.561	0.714
Cfe2	3.476	3.558	3.592	3.805	3.961	3.645	3.006	3.497	3.217	3.762	3.727	3.777	3.395	3.840	3.958	3.939	3.822	3.668
CMn	0.080	0.102	0.073	0.110	0.122	0.090	0.105	0.102	0.097	0.104	0.066	0.087	0.090	0.086	0.087	0.123	0.075	0.099
Sum_C	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
Bca	1.655	1.656	1.601	1.768	1.787	1.826	1.882	1.840	1.849	1.840	1.888	1.850	1.889	1.879	1.870	1.858	1.828	1.616
Bna	0.345	0.344	0.399	0.232	0.213	0.174	0.118	0.160	0.151	0.160	0.112	0.150	0.111	0.121	0.130	0.142	0.172	0.384
Sum_B	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ana	0.222	0.321	0.296	0.367	0.363	0.366	0.458	0.528	0.420	0.447	0.485	0.423	0.555	0.428	0.498	0.149	0.410	0.312
AK	0.217	0.212	0.211	0.204	0.167	0.273	0.216	0.243	0.245	0.240	0.233	0.249	0.268	0.301	0.266	0.145	0.253	0.184
Sum_A	0.439	0.532	0.507	0.571	0.529	0.639	0.674	0.771	0.665	0.686	0.718	0.672	0.823	0.729	0.764	0.294	0.664	0.495
Sum_cat	15.439	15.532	15.507	15.571	15.529	15.639	15.674	15.771	15.665	15.686	15.718	15.672	15.823	15.729	15.764	15.294	15.664	15.495
Mineral	(1)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(3)	(2)	(1)

Note. Analyzed by Zhou Jianxiong. FeO, total iron; (1), ferrohornblende; (2), ferro-edenite; (3), ferro-actinolite.

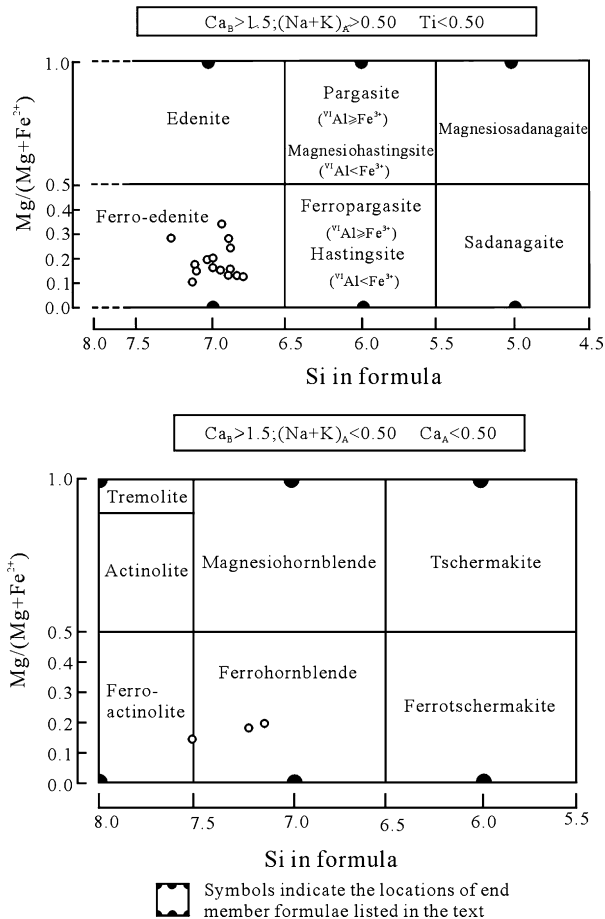


Fig. 4. Amphibole compositions from the Jiashan Syenite, Chengde (after Leake et al., 1997).

FeO contents (Fig. 6), indicating that the magma experienced fractional crystallization.

6.3. Rare earth elements

The REE data of the samples from the three units of the Jiashan Pluton are listed in Table 5 and a chondrite-normalized plot shown in Fig. 7. The Jiashan Syenite is characterized by high REE concentrations ($\Sigma\text{REE} = 237.86\text{--}450.38\text{ ppm}$), $\text{LREE/HREE} = 6.05\text{--}10.97$, $(\text{La}/\text{Sm})_{\text{N}} = 3.71\text{--}5.94$ and $(\text{La}/\text{Yb})_{\text{N}} = 10.33\text{--}14.91$. LREE and HREE are strongly fractionated (Fig. 7).

6.4. Trace elements

The contents of trace elements are listed in Table 6 and a primitive mantle-normalized multi-element diagram shown in Fig. 8. The Jiashan Syenite is depleted in Ba and Sr and such transitional elements as Cr, Co, Ni and V and enriched in high field strength elements (HFSE) like Nb, Zr and Hf, showing the character of an A-type granite (Whalen et al., 1996). The spiderdiagram of Fig. 8 shows that the three units have the same pattern and are significantly depleted in Ba, Sr, P and Ti.

Plots of $1000 \times \text{Ga}/\text{Al}$ ratios versus Ce, Zr, Y, and Nb are shown in Fig. 9. The diagrams in Fig. 9 show that rocks of the Jiashan Pluton have $1000 \times \text{Ga}/\text{Al}$ ratios of >3 and all plot in the field of A-type granites as determined by Whalen et al. (1987).

6.5. Sr and Nd isotopes

The Sr and Nd isotopic compositions of the Jiashan Syenite are listed in Table 7 and a plot of $(^{87}\text{Sr}/^{86}\text{Sr})_i$ versus $\varepsilon_{\text{Nd}}(t)$ is shown in Fig. 10. Rocks of the three units have low Sm/Nd values (0.1013–0.1166), and $^{143}\text{Nd}/^{144}\text{Nd}$ exhibit a narrow variation range from 0.512286 to 0.512456.

6.6. Discussion

The Jiashan Syenite has a high aluminium content with $\text{Al}_2\text{O}_3 = 15.02\text{--}16.5\%$ and an aluminium index (A/CNK) in the range of 0.84–0.99, indicating a metaluminous rock; the Alkali index (AI) (Wilson, 1989) is in the range of 2.56–4.47, showing that the rock belongs to the alkaline suite. To sum up, geochemically the Jiashan Syenite is rich in Si, alkalis, Fe and Al and poor in Mg and Ti. From the older unit to the younger unit, the SiO_2 content of the samples increases while $\text{K}_2\text{O} + \text{Na}_2\text{O}$ content decreases (Fig. 6).

The Jiashan Syenite is markedly enriched in LREE with significant negative Eu anomalies ($\delta\text{Eu} = \text{Eu}_{\text{N}}/[(\text{Sm} + \text{Gd})/2]_{\text{N}} = 0.36\text{--}0.70$), suggesting that plagioclase crystallized from the magma (Qiu et al., 2000; Li et al., 2001b). REE characteristics show a regular change: ΣREE contents increase and then decrease from the older unit to younger unit (the average value varies from 291.81 ppm, to 388.99 ppm, to 363.61 ppm), and the negative Eu anomaly is more significant in the younger unit. The three units have similar chondrite-normalized REE distribution patterns and the REE have similar fractionation and are concentrated in a very narrow field, showing that the rocks of the three units were derived from a common magma chamber (Kuang et al., 2001).

The troughs at Sr and Ti may be related to residual plagioclase and Fe–Ti oxides or earlier removal of Fe–Ti phases (Almeida et al., 2002). Significant enrichment of large ion lithophile elements such as Rb and Th is observed in the Jiashan Syenite. The Ga content is high with a high $10,000 \times \text{Ga}/\text{Al}$ ratio ranging from 3.15 to 3.60. The syenite plots within the A-type granite field in the Zr, Nb and Ce versus $\text{Y} \cdot 10^4 \times \text{Ga}/\text{Al}$ diagram of Whalen et al. (1987) (Fig. 9). The characteristics of the trace elements in the Jiashan Syenite are similar to the Yaokeng A-type granitoid of China (Qiu et al., 2000) and A-type granites in northeastern China (Wu et al., 2002).

The $\delta_{\text{Nd}}(t)$ exhibits a narrow variation range from -2.27 to -5.58 , showing that the magma of the three units were derived from the same source or from a single source (Wang et al., 2002). The initial ratios of $^{87}\text{Sr}/^{86}\text{Sr}$ of the Jiashan Syenite range from 0.701409 to 0.707405 with a mean of 0.70379, and fall in the range of the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios

Table 3

Electron microprobe analyses, atomic proportions and the end members of the representative clinopyroxene from Jiashan Syenite, Chengde

Unit	KJ						KL						KLn					
Sample	D260			D277			D262			D273			D261			D275		
Dot. No.	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
SiO ₂	48.91	49.46	48.59	49.05	49.54	49.35	48.73	49.63	49.78	50.00	49.72	49.21	50.13	49.23	50.47	48.96	48.90	48.58
TiO ₂	0.41	0.40	0.40	0.97	0.22	0.40	0.38	0.59	0.63	0.10	0.31	0.16	0.08	0.25	0.17	0.39	0.34	0.38
Al ₂ O ₃	0.57	0.68	0.60	2.11	0.52	0.53	0.93	1.12	1.90	0.66	1.25	1.31	0.30	0.31	0.27	0.72	1.14	0.64
Cr ₂ O ₃	0.03	0.08	0.12	0.23	0.13	0.01	0.10	0.01	0.00	0.45	0.00	0.18	0.11	0.01	0.07	0.15	0.46	0.10
FeO	23.33	20.83	23.08	22.64	22.48	22.97	21.90	19.67	18.46	31.92	33.13	32.20	19.70	20.20	20.28	23.70	22.77	23.42
MnO	0.82	0.88	0.80	0.77	0.86	1.14	0.87	0.70	0.66	0.92	1.28	1.19	0.90	1.03	0.93	0.96	0.75	1.06
MgO	3.84	4.98	3.81	5.41	4.00	3.65	4.47	5.84	7.60	2.12	1.76	1.77	5.95	5.96	5.90	4.26	4.93	4.10
CaO	20.91	21.41	20.80	17.15	21.09	20.68	20.98	21.22	18.99	11.33	11.40	10.88	21.60	21.10	21.37	19.83	19.48	19.81
Na ₂ O	0.43	0.41	0.43	0.92	0.46	0.56	0.53	0.39	0.84	0.55	0.59	0.71	0.31	0.29	0.23	0.40	0.21	0.37
K ₂ O	0.02	0.03	0.05	0.03	0.04	0.00	0.00	0.02	0.24	0.08	0.45	0.60	0.05	0.08	0.00	0.02	0.03	0.04
Total	99.27	99.16	98.68	99.28	99.37	99.29	98.89	99.19	99.10	98.13	99.89	98.21	99.13	98.46	99.69	99.39	99.01	98.50
<i>Number of cations per 6 oxygens</i>																		
TSi	1.973	1.979	1.972	1.954	1.992	1.991	1.961	1.972	1.950	2.102	2.055	2.064	1.994	1.975	2.002	1.973	1.972	1.977
TAI	0.027	0.021	0.028	0.046	0.008	0.009	0.044	0.052	0.088	0.033	0.061	0.065	0.014	0.015	0.013	0.034	0.054	0.031
M1Al	0.000	0.011	0.000	0.053	0.017	0.016	0.006	0.024	0.038	0.033	0.061	0.065	0.008	0.000	0.013	0.008	0.026	0.008
M1Ti	0.012	0.012	0.012	0.029	0.007	0.012	0.011	0.018	0.019	0.003	0.010	0.005	0.002	0.008	0.005	0.012	0.010	0.012
M1Fe ²⁺	0.754	0.678	0.751	0.585	0.732	0.751	0.687	0.654	0.554	1.122	1.145	1.129	0.640	0.631	0.673	0.775	0.768	0.777
M1Cr	0.001	0.003	0.004	0.007	0.004	0.000	0.003	0.000	0.000	0.015	0.000	0.006	0.003	0.000	0.002	0.005	0.015	0.003
M1Mg	0.231	0.297	0.230	0.324	0.240	0.219	0.268	0.346	0.444	0.133	0.108	0.111	0.353	0.356	0.349	0.256	0.296	0.249
M1Ni	0.002	0.000	0.002	0.002	0.001	0.001	0.000	0.000	0.000	0.000	0.002	0.002	0.000	0.001	0.003	0.002	0.002	0.001
M2Fe ²⁺	0.034	0.019	0.032	0.169	0.024	0.024	0.024	0.042	0.105	0.306	0.323	0.314	0.023	0.032	0.023	0.078	0.115	0.068
M2Mn	0.028	0.030	0.027	0.026	0.029	0.039	0.030	0.024	0.022	0.033	0.045	0.042	0.030	0.035	0.031	0.033	0.026	0.037
M2Ca	0.904	0.918	0.904	0.732	0.909	0.894	0.904	0.903	0.797	0.510	0.505	0.489	0.921	0.907	0.908	0.856	0.842	0.864
M2Na	0.034	0.032	0.034	0.071	0.036	0.044	0.041	0.030	0.064	0.045	0.047	0.058	0.024	0.023	0.018	0.031	0.016	0.029
M2K	0.001	0.002	0.003	0.002	0.002	0.000	0.000	0.001	0.012	0.004	0.024	0.032	0.003	0.004	0.000	0.001	0.002	0.002
Sum_cat	3.999	3.998	3.997	3.998	3.998	4.000	4.000	3.999	3.998	3.996	3.976	3.968	3.997	3.996	4.000	3.999	3.998	3.998
<i>End members</i>																		
Wo	46.352	47.269	46.482	39.871	46.990	46.379	46.734	46.892	42.697	28.380	28.053	27.671	46.990	45.951	46.424	44.134	43.615	44.426
En	11.844	15.298	11.847	17.630	12.400	11.390	13.640	17.956	23.766	7.389	5.821	6.016	18.010	17.938	17.952	13.006	15.265	12.700
Fs	41.804	37.432	41.627	42.499	40.610	42.231	39.617	35.151	33.556	64.231	66.126	66.314	41.084	37.432	41.672	42.860	41.121	42.875
Mineral	(1)	(1)	(1)	(2)	(1)	(1)	(1)	(1)	(2)	(2)	(2)	(2)	(1)	(1)	(1)	(2)	(2)	(2)

Note. Analyzed by Zhou Jianxiong. FeO, total Fe. (1), hedenbergite; (2), augite.

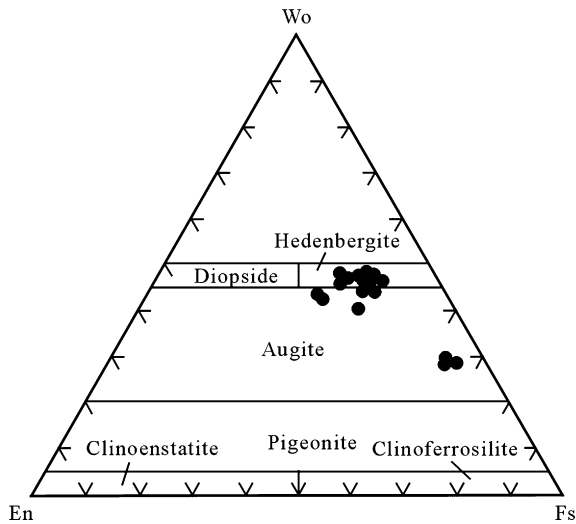


Fig. 5. Clinopyroxene composition from the Jianshan Syenite, Chengde (after Morimoto et al., 1988).

of the modern oceanic basalt ($I_{\text{Sr}} = 0.702\text{--}0.706$, Faure, 1986). In the $(^{87}\text{Sr}/^{86}\text{Sr})_i - \delta_{\text{Nd}}(t)$ diagram (Fig. 10), the Jianshan Syenite falls between the undifferentiated mantle field and the EM I field, away from the lower crust and upper crust fields of North China, indicating that magma was derived mainly from enriched lithospheric mantle, with some minor primitive mantle component. The initial ratios of $^{87}\text{Sr}/^{86}\text{Sr}$ of the Jianshan Syenite span a large range, which might imply that they originated from metasomatised lithospheric mantle (Wang and Zhao, 1997). The magmas of the Qiancengbei, Shanhaiguan, Kulongshan and Xiangshan A-type granites in the region were also derived from the lithospheric mantle (Li, 2002). The geochemistry of mantle-derived xenoliths of Mesozoic basic rock, Cretaceous volcanic rock (124–119 Ma) and Cenozoic basalt in the North

China region indicate that the lithospheric mantle beneath the North China Plate is of EM I type (Chen et al., 1997; Jahn et al., 2001; Guo et al., 2001; Hong et al., 2003).

In the Yb versus Ta diagram (Fig. 11), the samples from the three units of the Jianshan Pluton fall in the within-plate granite field defined by Pearce et al. (1984) for Phanerozoic granites. Similar to Cretaceous A-type granites in the Yanshan Belt, the Jianshan Pluton falls in the field of the SiO_2 versus $\text{Lg}[\text{CaO}/(\text{K}_2\text{O} + \text{Na}_2\text{O})]$ diagram (Fig. 12), suggesting that the Jianshan Pluton was emplaced in an extensional tectonic setting. In the R_1 versus R_2 diagram (Fig. 13), the Jianshan samples plot within the late-orogenic field.

7. A-type granites

A-type granites have been divided into A_1 (anorogenic) type and A_2 (post-orogenic) type (Eby, 1992; Eby and Kochhar, 1990; Hong et al., 1996). Both are formed in tensional stress regimes (Hong et al., 1996). A_1 -type granite is mantle-derived and emplaced in an anorogenic setting such as continental rifts or other intraplate environment, while A_2 -type granite is derived from melting of continental crust or underplated mafic crust and emplaced in a variety of tectonic environment (Eby, 1992; Eby and Kochhar, 1990; Wu et al., 2002). Hong et al. (1996) suggested that AA -type granite (anorogenic) is independent of subduction and collision, tends to be associated with lithospheric rifting, and is often closely associated with mafic rocks and silica-undersaturated syenites. PA -type granite (post-orogenic) is formed shortly after plate subduction and plate collision, commonly associated with ophiolitic plate suture zones, and is associated with the calc-alkaline series.

The geochemical characteristics of the Jianshan Syenite indicate that it is an A-type granite. More specifically, the

Table 4
Major elements (%) of each unit from Jianshan Syenite, Chengde

Unit	KJ						KL					KLn			
Sample	D260	D272	D277	YQ060	YQ061	YQ067	YQ063	YQ066	D262	D276	D273	D261	D275	YQ065	
SiO_2	62.73	63.15	62.13	63.09	62.37	61.34	66.46	65.19	64.83	63.62	66.25	65.85	64.77	65.82	
TiO_2	0.57	0.53	0.74	0.37	0.42	0.8	0.38	0.35	0.51	0.75	0.44	0.7	0.55	0.74	
Al_2O_3	16.2	16.5	15.9	16.36	16.14	15.5	15.66	15.49	15.9	16	16.1	15.4	16.1	15.02	
FeO	3.84	3.92	4.06	2.21	2.4	3.88	0.4	1.82	3.01	3.56	1.92	3	2.72	2.19	
Fe_2O_3	2.13	2	2.54	3.48	3.64	3.16	3.98	2.7	1.64	1.52	2.42	1.45	2.37	2.98	
MnO	0.17	0.17	0.18	0.14	0.18	0.2	0.12	0.12	0.12	0.13	0.11	0.11	0.12	0.12	
CaO	2.19	2.12	2.51	1.96	2.14	2.7	1	1.66	1.84	2.41	1.13	2.14	1.42	2.18	
MgO	0.3	0.2	0.6	0.31	0.41	0.62	0.16	0.53	0.3	0.7	0.1	0.7	0.2	0.72	
K_2O	5.6	5.64	5.34	5.99	5.94	5.27	5.64	5.59	5.35	5.1	5.66	5.18	5.52	4.95	
Na_2O	5.2	5.6	5.1	5.57	5.47	5.47	5.32	5.56	4.9	5.3	4.6	5.4	4.8	5	
P_2O_5	0.14	0.13	0.2	0.12	0.12	0.1	0.12	0.09	0.12	0.21	0.09	0.19	0.14	0.11	
H_2O^+	0.48	0.55	0.66						0.3	0.68	0.59	0.44	0.36		
H_2O^-				0.16	0.09	0.05	0.06	0.11						0.07	
Los				0.71	0.64	1.02	1.02	0.96						0.41	
CO_2	0.18	0.11	0.66						0.73	0.73	0.33	0.07	0.33		
Corg	0.09	0.07	0.12						0.07	0.05	0.03	0.03	0.14		
Total	99.82	100.7	100.7	100.5	99.96	100.11	100.32	100.88	99.62	100.7	99.77	100.7	99.54	100.31	
A/CNK	0.87	0.87	0.85	0.85	0.83	0.79	0.94	0.85	0.93	0.86	0.98	0.84	0.99	0.85	

Note. Sample YQ060, YQ061, YQ067, YQ063, YQ066 and YQ065 after Yang and Li (1997).

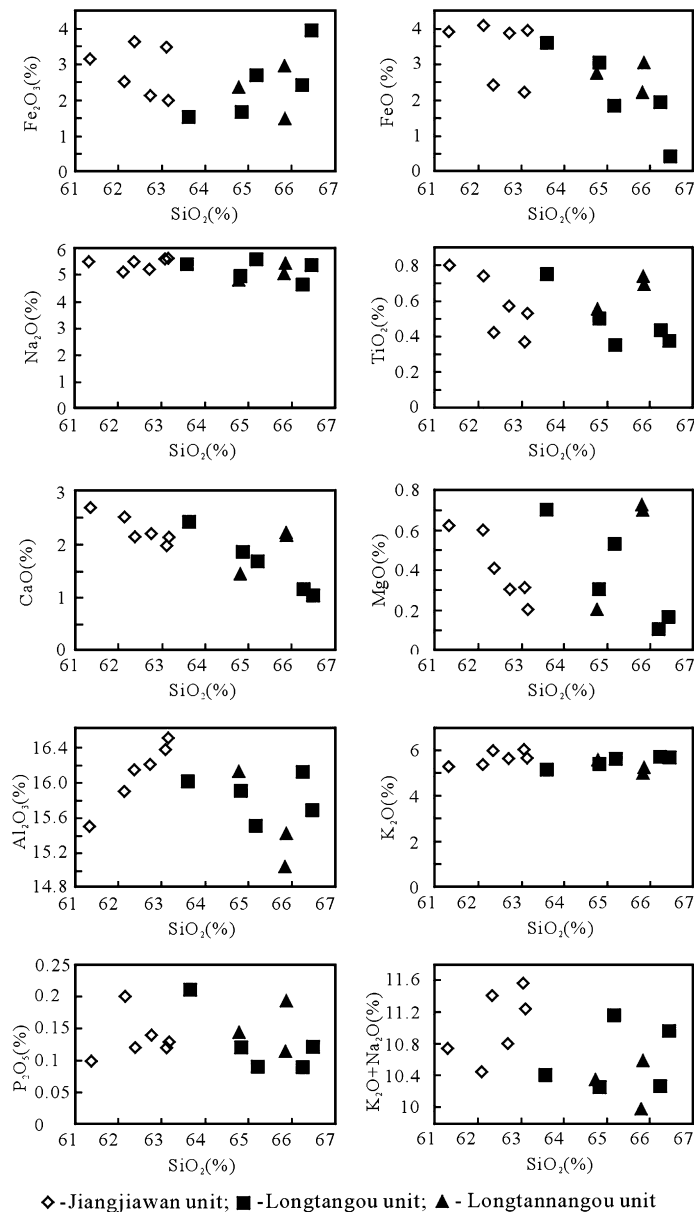


Fig. 6. Harker diagrams of major elements for the Jiashan Syenite, Chengde.

Jiashan Syenite falls in the A₁-granite field (Fig. 14) of the Nb–Y–Ce discriminant diagram (Eby, 1992; Eby and Kochhar, 1990) and plots within the range of the Wulingshan, Qiancengbei, Shanhaiguan and Xiangshan A-type granites in Yanshan area, suggesting an anorogenic setting. In the R_1 and Ga/Al diagram suggested by Hong et al. (1995), the samples fall in the AA field, indicating that the pluton formed in a continental rift tectonic setting. From the existing structural data, we cannot confirm whether the emplacement of the Jiashan Pluton is related to a continental rift environment, but we suggest that the magma was derived from the mantle and was emplaced during an extensional regime. The magma of the Wulingshan Syenite was derived from the lithospheric mantle and had undergone fractional crystallization (Li, 2002). Similarly, the Jiashan Pluton was emplaced in lithospheric extensional

environment, and magmatism is related to upwelling of asthenospheric material resulting from lithospheric thinning.

Cretaceous alkaline intrusive complexes are widespread in the southern portion of the North China Craton, such as Hongshan complex and Longbaoshan complex. They were derived from the partial melting of previously subduction-modified lithospheric mantle, in response to post-collisional lithospheric extension and asthenospheric upwelling (Zhang et al., 2005). The lithospheric extension and subsequent asthenosphere upwelling resulted in decompressional melting of these hydrous rocks in the mantle in the Late Jurassic to Early Cretaceous (Zhang et al., 2005). A-type granites are also widely distributed in northeastern China, where they were emplaced during three major episodes (the Permian, Late

Table 5
Rare earth elements compositions (ppm) of each unit from Jiashan Syenite, Chengde

Unit	KJ				KL				KLn		
Sample	D260	D272	D277	P50XT27	D262	D276	D273	P50XT11	D261	D275	P50XT21
La	53	68	72	67.9	108	73	115	75.19	96	78	94.43
Ce	92	120	140	114.7	185	134	175	138	148	142	158.4
Pr	12.3	15.5	17.3	11.95	21.4	15.4	23.8	15.45	19.5	16.7	15.61
Nd	45.8	57.6	65.3	50.98	73.1	55.8	83.4	67.02	67	59.4	62.15
Sm	8.6	10.6	12.2	8.57	12.5	9.8	14	12.2	11.3	10.8	10.01
Eu	1.85	2.18	2.47	1.97	1.72	2.03	1.55	2.18	1.68	1.87	1.51
Gd	7.7	9.2	10.8	8.55	11.1	8.8	12	11.2	10	9.3	9.52
Tb	1.21	1.48	1.74	1.31	1.77	1.41	1.88	2	1.63	1.49	1.73
Dy	6.3	7.5	8.8	6.88	9.5	7.3	9.6	10.12	8.5	8	8.16
Ho	1.29	1.51	1.88	1.45	1.97	1.53	1.96	2.11	1.79	1.71	1.77
Er	3.2	3.9	4.7	4.07	5.5	4.1	5.2	5.78	4.9	4.4	5.06
Tm	0.6	0.7	0.81	0.57	1	0.71	0.91	0.76	0.88	0.81	0.7
Yb	3.4	4	4.7	3.7	5.7	4.1	5.2	4.85	4.9	4.5	4.51
Lu	0.61	0.68	0.75	0.49	0.95	0.67	0.88	0.81	0.8	0.75	0.63
LREE	213.6	273.88	309.27	256.07	401.7	290.03	412.8	310.04	343.48	308.77	342.11
HREE	24.31	28.97	34.18	27.02	37.49	28.62	37.63	37.63	33.4	30.96	32.08
LR/HR	8.78	9.45	9.05	9.48	10.72	10.13	10.97	8.24	10.28	9.97	10.66
ΣREE	237.9	302.85	343.45	283.09	439.2	318.65	450.4	347.67	376.88	339.73	374.19
(La/Sm) _N	3.88	4.04	3.71	4.99	5.44	4.69	5.17	3.88	5.34	4.54	5.94
(La/Yb) _N	10.51	11.46	10.33	12.37	12.78	12	14.91	10.54	13.21	11.69	14.1
δEu	0.68	0.66	0.64	0.70	0.44	0.66	0.36	0.56	0.47	0.56	0.47

Note. Sample P50XT27, P50XT11 and P50XT21 after Yang and Li (1997).

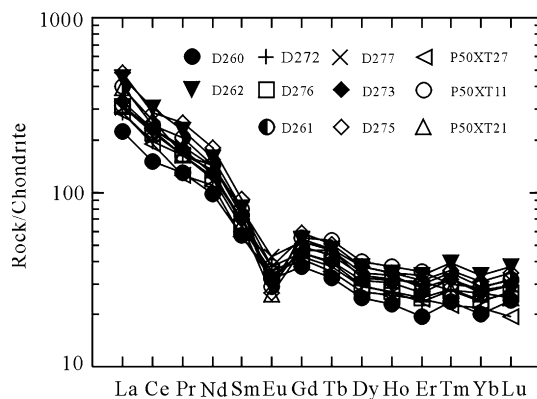


Fig. 7. Chondrite-normalized REE patterns of the Jiashan Syenite, Chengde (normalizing factors after Boynton, 1984).

Triassic to Early Jurassic, and Early Cretaceous) and evolved in different tectonic environments. The early Cretaceous A-type granites have an anorogenic affinity and were possibly associated with rifting in eastern China at this time, associated with the onset of paleo-Pacific subduction (Wu et al., 2002).

8. A-type granites and timing of lithosphere thinning in China

Intraplate orogeny was intense in the Yanshan area in the Middle–Late Jurassic, which according to Davis et al. (1998) is manifested by N–S crustal shortening, indicated by large-scale overthrusting and folding at 161–132 Ma, and attendant lithospheric thickening. The Early Cretaceous Zhangjiakou Formation is a suite of felsic volcanics, widely distributed in northern Hebei Province and

Table 6
Trace elements (ppm) of the Jiashan Syenite

Unit	KJ			KL			KLn	
Sample	D260	D272	D277	D262	D276	D273	D261	D275
Sr	72	83	112	148	214	114	180	167
Rb	102	108	102	170	136	174	178	149
Ba	533	537	555	563	855	447	647	631
Th	6.3	7.0	7.4	20.3	10	14.8	18	10.9
U	1.22	1.48	1.52	4.88	2.59	2.11	3.53	1.7
Cr	5.0	5.3	5.0	5.0	6.2	5.0	5.0	5.0
Ta	3.63	4.24	4.93	7.52	4.58	6.65	6.6	5.31
Nb	54.2	64.5	77.5	97.9	65.9	97.4	89.5	80.2
Zr	353	295	493	701	502	633	537	585
Hf	11.2	9.7	15.8	25.8	18.4	21.7	14.3	21.9
Cu	6.5	6.7	9.5	5.3	8.1	7.6	9.5	5.7
Pb	8.5	10.7	12.8	13.8	15.9	17.8	24.2	13.3
Zn	120	117	127	107	118	113	100	98
Mo	2.71	2.95	3.22	4.17	3.76	2.93	4.01	1.93
V	19.9	16.3	25.3	24	26.5	18.9	29.3	8.9
Ni	5.6	7.9	6.6	5.9	5.8	6.1	5.7	2.9
Y	31.5	37.5	45.6	51.1	38.5	48.7	46.4	41.5
Co	1.6	1.8	3.9	2.1	3.9	1.7	4.8	2.6
Ga	30.2	30.7	30	29.8	27.8	29.9	25.7	28.6
Sc	6.4	6.9	8.7	4.6	5.6	4.1	6	4.6

Note. Sr, Rb, Ba, Cr, Nb, Zn, V, Ni, Ga were determined by using the X-ray fluorescence spectrometry (XRF) and other trace elements were measured with ICP-MS.

adjacent area. The Zhangjiakou Formation can be subdivided into three lithological members: the lower member consists of rhyolite, rhyolitic tuff and ignimbrite; the middle member is predominantly of andesite and trachyandesite; and the upper member is composed of rhyolitic–trachytic–trachyandesitic lavas, volcanic tuff, tuffaceous conglomerate and ignimbrite. This suggests that the evo-

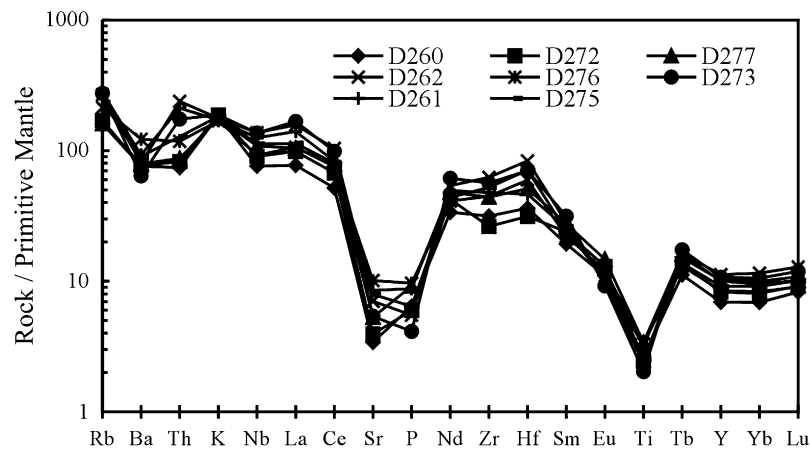


Fig. 8. Primitive mantle-normalized trace element spiderdiagrams for the Jiashan Syenite, Chengde (normalizing factors after Sun and McDonough, 1989).

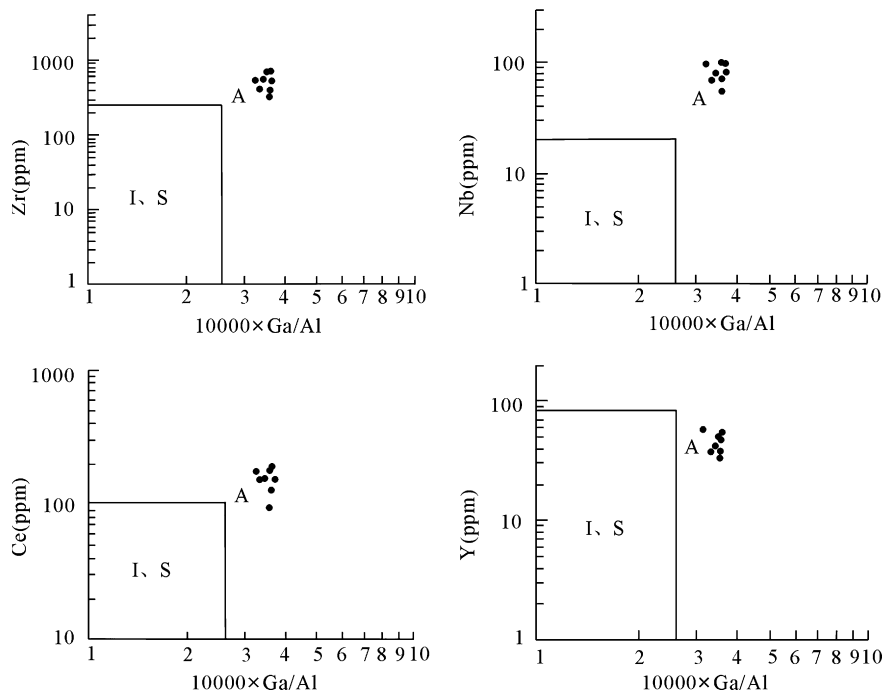


Fig. 9. Zr, Nb, Ce and Y–10⁴ × Ga/Al diagrams of the Jiashan Syenite, Chengde (diagram and field of A-type granites from Whalen et al., 1987).

Table 7
Sr and Nd isotopic compositions of the Jiashan Syenite, Chengde

Unit	Sample	Rb (ppm)	Sr (ppm)	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr (2σ)	<i>t</i> (Ma)	<i>I</i> _{Sr}	Sm (ppm)	Nd (ppm)	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd (2σ)	ε _{Nd} (<i>t</i>)	<i>T</i> _{DM} (Ma)
KJ	D260					113		8.822	46.153	0.1156	0.512360 ± 9	–4.25	1226
KJ	D272	140.4	61.89	6.566	0.712666 ± 13	113	0.702122	8.603	48.186	0.1080	0.512456 ± 7	–2.27	1234
KJ	D277	171.7	92.40	5.380	0.710049 ± 14	113	0.701409	9.909	51.388	0.1166	0.512379 ± 9	–3.40	1118
KL	D262	116.9	132.2	2.559	0.711514 ± 15	113	0.707405	11.032	65.857	0.1013	0.512325 ± 10	–4.73	1001
KL	D276	183.7	190.2	2.797	0.709121 ± 15	113	0.704629	10.086	54.572	0.1118	0.512421 ± 10	–3.01	1216
KL	D273	187.3	89.90	6.033	0.713121 ± 13	113	0.703433	12.767	69.172	0.1116	0.512335 ± 8	–4.68	1204
KLn	D261	164.9	162.1	2.946	0.710803 ± 13	113	0.706072	10.468	59.142	0.1071	0.512286 ± 6	–5.58	1090
KLn	D275	283.6	142.7	5.755	0.710692 ± 14	113	0.701450	9.994	54.369	0.1112	0.512340 ± 8	–4.58	1209

Note. Analyzed by Tang Suohan and Wang Jinhui.

lution of volcanism of the Zhangjiakou Formation from felsic to intermediate and subalkaline (Niu et al., 2004). Geochemically, the rhyolite of the Zhangjiakou Formation is enriched in silica, K₂O, REE and LREE with a pro-

nounced Eu negative anomaly. The genesis of volcanic rocks of the Zhangjiakou Formation is related to partial melting of the lower crust caused by underplating (Shao et al., 2003). The Early Cretaceous Zhangjiakou Forma-

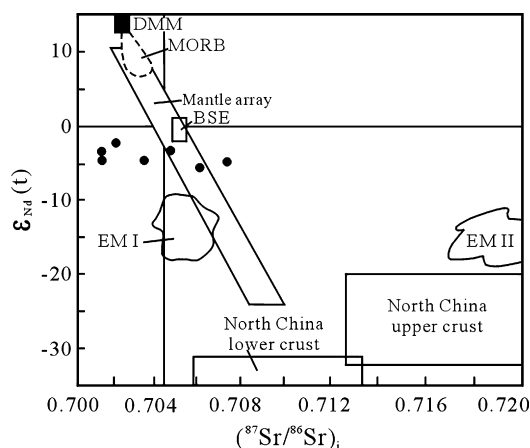


Fig. 10. $(^{87}\text{Sr}/^{86}\text{Sr})_i$ versus $\epsilon_{\text{Nd}}(t)$ diagram for the Jiashan Syenite, Chengde (EMI and EMII after Zindler and Hart, 1986; North China lower crust and upper crust after Jahn et al., 1999).

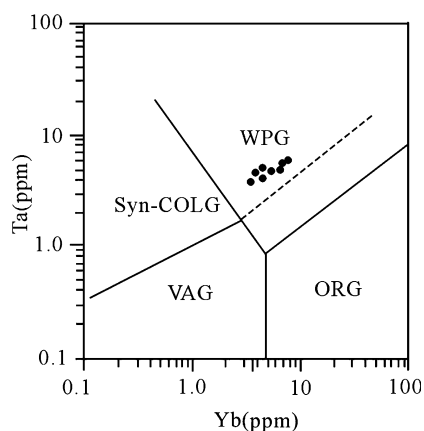


Fig. 11. Yb versus Ta diagram for the Jiashan Syenite, Chengde (after Pearce et al., 1984). WPG, within plate granites; ORG, ocean ridge granites; VAG, volcanic arc granites; Syn-COLG, syn-collision granites.

tion and Yixian Formation volcanic units developed in the Yanshan Belt, the volcanic event occurred in the post-orogenic extensional setting in the early Early Cretaceous, being of post-orogenic volcanic series (Niu et al., 2004), indicating that the intense thrusting and folding deformation in the Late Jurassic had ended (Beijing Bureau of Geology and Mineral Resources, 1991; Chen et al., 1997; Davis et al., 2001; Zhao et al., 2004). The gently dipping Lower Cretaceous Zhangjiakou Formation felsic volcanic and sedimentary clastic rocks unconformably overlie the Chengde Thrust sheet (Davis et al., 1998) at Jiguanshan, Chengde County (Fig. 15). The SHRIMP zircon U–Pb age of welded tuff at the base of the Zhangjiakou Formation is 135 ± 1 Ma (Zhao et al., 2004) and K-feldspar from a trachyte flow in this formation gives a ^{40}Ar – ^{39}Ar plateau age of 122.5 ± 5.5 Ma (Davis et al., 2001). This suggests that crustal shortening and contractional deformation had ended before 135 Ma in this area. Widespread regional extensional deformation occurred within the Yanshan Belt in the Early Cretaceous (<135 Ma).

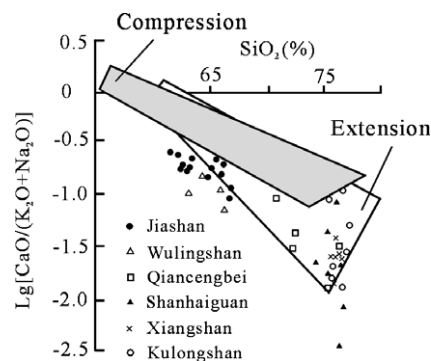


Fig. 12. SiO_2 – $\text{Lg} [\text{CaO}/(\text{K}_2\text{O} + \text{Na}_2\text{O})]$ diagram for the Jiashan Syenite, Chengde (after Brown, 1982), data are from Li (2002) except for Jiashan data.

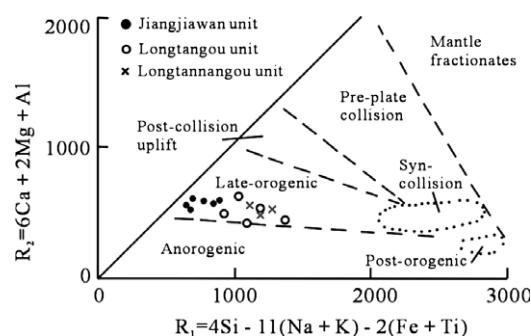


Fig. 13. Diagram R_1 – R_2 multiple cations for the Jiashan Syenite, Chengde (after Batchelor and Bowden, 1985).

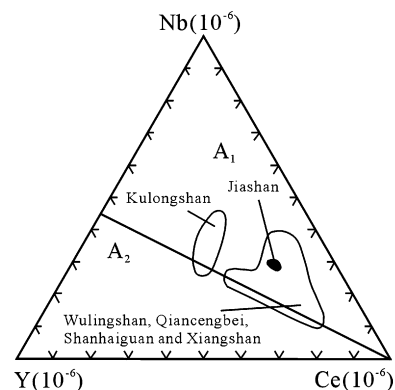


Fig. 14. Nb–Y–Ce discriminant diagram of the Jiashan Syenite, Chengde (after Eby and Kochhar, 1990). Data from the Wulingshan, Qiancengbei, Shanhaiguan, Xiangshan and Kulongshan A-type granites after Li (2002). A₁, anorogenic A-type granite; A₂, post-orogenic A-type granite.

The Yanshan Belt, as well as other regions of eastern and northeastern China (Wu et al., 2002; Zhang et al., 2005), contains several A-type alkaline to peralkaline intrusions, ranging in age from <135 to ~80 Ma (Xu et al., 1994; Yu et al., 1994; Davis et al., 2001; Wang and Zhang, 2001; Li, 2002). The occurrence of these A-type granites demonstrates that the lithosphere beneath the region must have been considerably thinned at the time of intrusion of

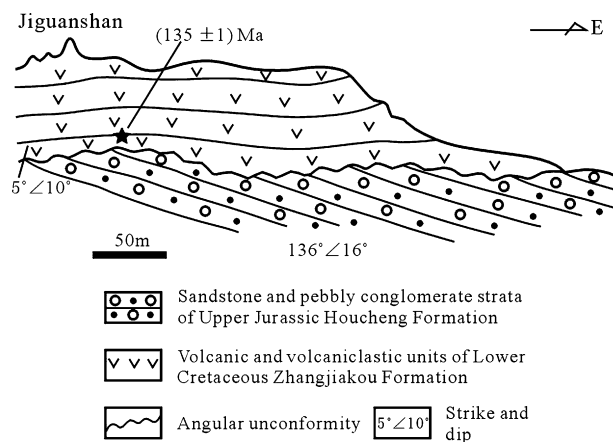


Fig. 15. Angular unconformity beneath the Zhangjiakou Formation across northern limb of Chengde synform (after Zhao et al., 2004). See Fig. 1b for location.

these plutons (Zhang et al., 2005). Based on the spatial distribution and geochemical comparison, Fan and Guo (2005) argue that the intensive mafic magmatism in late Mesozoic in the eastern part of North China Block occurred in a lithospheric thinning and extensional environment.

Huang et al. (1977), Ren et al. (1980) and Bao et al. (1983) suggested that compressive deformation culminated in the period from the end of the Jurassic to the beginning of the Early Cretaceous in eastern China and then was transformed into extensional deformation, which was a significant transition period in the Mesozoic–Cenozoic geodynamic evolution of eastern China.

Data from the Jiashan Syenite confirm this conclusion. Based on the study of the Jiashan Syenite, we further suggest that the regional Late Jurassic compressional shortening and crustal thickening had ended before 135 Ma, and was followed by regional extension and lithospheric thinning (<135 Ma). Deng et al. (2004) proposed that the western orogenic belt is not genetically related to eastern continental rifting. However, we argue that such a relationship is consistent with a model of anorogenic rifting, associated with delamination of thickened lithospheric mantle, resulting in upwelling of asthenospheric mantle beneath eastern China, engendering lithospheric thinning, eruption of high-K, calc-alkaline, intermediate-basic volcanic rocks, intrusion of diabase dikes and A-type granites and formation of downfaulted basins. The post-orogenic large-scale eruption of volcanics and emplacement of A-type granites in the Early Cretaceous marks the closure of the Paleo-Pacific dynamic system and the onset of the new Pacific dynamic system, since the Late Cretaceous (Niu et al., 2004). The Jiashan Syenite records the geological process during regional extension and lithospheric thinning in the Early Cretaceous. It and coeval A-type intrusions have considerable significance for revealing the features and evolution of the Late Mesozoic lithosphere in the Yanshan area and eastern China.

9. Conclusions

1. Geochemically, the Jiashan Syenite is rich in Si, alkalis, Fe_{total} , Al, REE, Nb, Zr, Ga and Hf and poor in Mg, Ba, Sr and Ti and such transition elements as Cr, Co, Ni and V, with a high Ga/Al ratio. Its Ce/Pb ratio ranges from 6.12 to 13.41 and it is enriched in LREE with a moderate Eu negative anomaly. The $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios of the rock ranges from 0.701409 to 0.707405 with a mean of 0.70379, and the $\delta_{\text{Nd}}(t)$ values range from -2.27 to -5.58 , indicating that the magma was derived from enriched mantle.

2. The Jiashan Syenite can be considered as A_1 -type granite. It was emplaced in a late-orogenic lithospheric extensional environment and the emplacement was related to upwelling of asthenospheric mantle. The Jiashan Syenite is located on the eastern side of the Late Jurassic Chengde Thrust Sheet and originated in the late Early Cretaceous, suggesting that the regional Late Jurassic compressional shortening and crustal thickening had ended before 135 Ma, and regional extension and lithospheric thinning began. The Jiashan Syenite and similar intrusions in north-eastern China represent a record of lithospheric thinning in the Yanshan Intracontinental Orogenic Belt.

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