

Petrogenesis of the Middle Devonian Gushan diorite pluton on the northern margin of the North China block and its tectonic implications

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Abstract – The Gushan diorite pluton, located at the northern margin of the North China block, was emplaced during Middle Devonian times (SHRIMP U–Pb zircon age of 390 ± 5 Ma). Rocks from the pluton are characterized by low SiO_2 and high alkali contents, and they show monzodiorite compositions in a total alkali v. silica (TAS) plot. They exhibit light REE-enrichment, no to slightly positive Eu anomalies, strong depletion in Rb, Th, U, Nb, Ta, P, Zr, Hf and Ti, enrichment in Ba, K and Sr, low contents of Y and Yb, and high Sr/Y ratios. They have a relatively narrow range of isotopic compositions with initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of ~ 0.7050 , $\varepsilon_{\text{Nd}}(\text{T})$ values of -9.5 to -7.5 and zircon $\varepsilon_{\text{Hf}}(\text{T})$ values from -11.8 to -5.8 . These features are remarkably similar to another Middle Devonian intrusion, the Shuiquangou syenitic complex at the northern margin of the North China block. These similarities suggest that the two intrusions probably have a common origin. They were considered to be derived from a type I enriched mantle, ultimately with some involvement of ancient lower crustal components, and were likely emplaced in a back-arc extension environment related to southward subduction of the Palaeo-Asian oceanic plate or during the cessation of the subduction. Aluminium-in-hornblende barometry studies of the Middle Devonian Gushan pluton yielded emplacement depths of about 18 km. Combined with previous geobarometry results on the Carboniferous plutons within the Inner Mongolia Palaeo-uplift on the northern margin of the North China block, it is inferred that the uplift and exhumation of the plutons within the Inner Mongolia Palaeo-uplift during Middle Devonian to Late Carboniferous times were not as distinct as those during Late Carboniferous to Early Jurassic times, and the strong uplift and exhumation of the Inner Mongolia Palaeo-uplift were achieved during Late Carboniferous to Early Jurassic times.

Keywords: diorite, petrogenesis, Devonian, North China block.

1. Introduction

The North China block (or North China Craton) was usually regarded as a Precambrian craton finally amalgamated during Palaeoproterozoic times, around 1.85 Ga, as a result of continental–continental collision between the Eastern block and the Western block (Zhao *et al.* 2001; Wilde, Zhao & Sun, 2002). Traditionally, the tectonic history of the North China block has been considered to be stable from Neoproterozoic through to Triassic times (e.g. Ren *et al.* 1990; Song, 1999). However, recent geological and geochronological data reveal that the northern margin of the North China block was influenced by the Palaeo-Asian tectonic domain during Carboniferous to Permian times (e.g. Wang, 1996; Cui & Wu, 1997; Davis *et al.* 2001; Xiao *et al.* 2003). A Carboniferous Andean-style continental arc was distinguished from the Precambrian craton in the northern margin of the North China block (Zhang *et al.* 2007), which was strongly eroded during

Late Carboniferous to Early Jurassic times (Zhang, Zhao & Song, 2006). These investigations made some contributions to the Carboniferous–Permian tectonic history of this area, but the tectonic and magmatic history prior to Carboniferous times is still poorly understood. The newly identified Middle Devonian intrusions from the Archaean to Palaeoproterozoic terrain at the northern margin of the North China block provide a new means to define the tectonic event of the North China block and the Central Asian Orogenic Belt. In this paper, we present some new data in petrology, mineral chemistry, zircon SHRIMP (Sensitive High Resolution Ion MicroProbe) U–Pb geochronology, *in situ* zircon Lu–Hf and whole-rock Sr–Nd isotopes, and emplacement depth of a Middle Devonian pluton to give some new constraints on the tectonic and magmatic history of the northern margin of the North China block during early Late Palaeozoic times.

2. Geological setting

The northern margin of the North China block, located to the southeast of the Central Asian Orogenic Belt,

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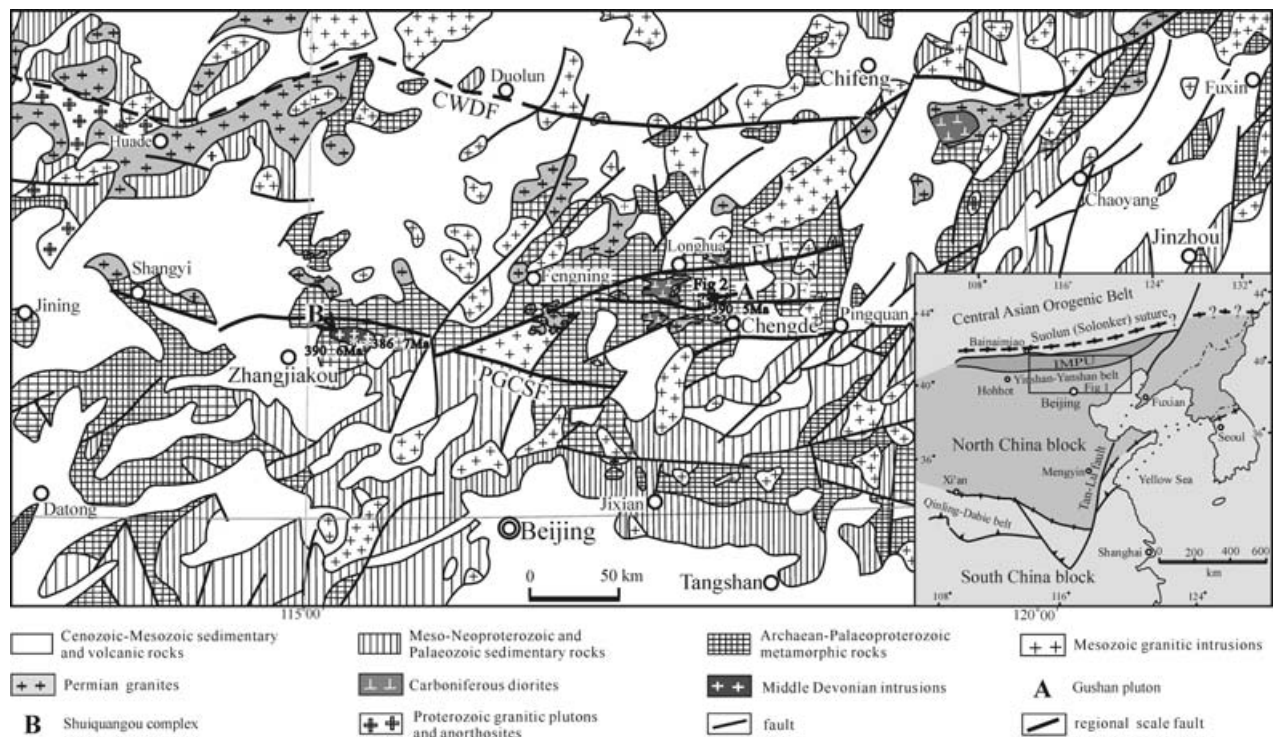


Figure 1. Geological sketch map of the northern margin of the North China block (modified after Zhang *et al.* 2007; index figure modified after Davis *et al.* 2001). PGCSF – Pingquan–Gubeikou–Chicheng–Shangyi fault; DF – Damiao fault; FLF – Fengning–Longhua fault; CWDF – Chicheng–Weichang–Duolun fault; IMPU – Inner Mongolia Palaeo-uplift.

is separated by the Pingquan–Gubeikou–Chicheng–Shangyi fault into two E–W-trending tectonic units of the Inner Mongolia Palaeo-uplift (also called ‘the Inner Mongolia Axis’: Huang, 1945) in the north and the Yanshan thrust-and-fold belt (Hebei Bureau of Geology and Mineral Resources, 1989; Davis *et al.* 2001) in the south (Fig. 1). The Inner Mongolia Palaeo-uplift is characterized by extensive early Precambrian high-grade basement rocks that are unconformably overlain by Jurassic–Cretaceous volcanic and sedimentary rocks, and is a tectonic province strongly exhumed during Late Carboniferous to Early Jurassic times (Zhang *et al.* 2007; Zhang, Zhao & Song, 2006).

Mesozoic and early Precambrian (Archaean and Palaeoproterozoic) intrusions are widely distributed within the northern margin of the North China block. Some Permian and Carboniferous granitoids were identified from the early Precambrian basement rocks within the Inner Mongolia Palaeo-uplift during the last two decades (e.g. Hebei Bureau of Geology and Mineral Resources, 1989; Hong *et al.* 1995; Cui & Wu, 1997; Liaoning Bureau of Geology and Mineral Resources, 1989; Pan, 1996; Kröner *et al.* 2004; Zhang *et al.* 2004a, b; Zhang *et al.* 2007), but Palaeozoic intrusions prior to Carboniferous times were rarely reported except for the Middle Devonian Shuiquangou complex (Luo *et al.* 2001). Our new SHRIMP U–Pb dating recognized a Devonian diorite pluton near Gushan within the Inner Mongolia Palaeo-uplift (Figs 1, 2; see following discussions).

The Gushan diorite pluton is located at the north wall of the Damiao fault within the Inner Mongolia Palaeo-uplift, with an area of about 10 km² (Fig. 1). The pluton is unconformably overlain by the Lower Jurassic Nandaling Formation (volcanic rocks) and Xiahuayuan Formation (coal-bearing sedimentary rocks; Fig. 2) in the middle-eastern part, and intruded into the Archaean metamorphic rocks and Palaeoproterozoic anorthosite and norite (Zircon SHRIMP U–Pb age of the anorthosite is 1726 ± 9 Ma, 95 % confidence, MSWD = 0.93, N = 12: S. H. Zhang, unpub. data). It had been previously considered as a Precambrian (Hebei Bureau of Geology and Mineral Resources, 1974), Mesozoic (Xie, 1980) or Late Palaeozoic (Hebei Bureau of Geology and Mineral Resources, 1989, 1994) intrusion.

3. Petrology and sample description

3.a. Petrology of the Gushan pluton

The Gushan pluton is relatively homogeneous in terms of petrographic textures and mineral assemblages. Main rock types are medium-grained quartz monzodiorite and monzodiorite, and they show a hypidiomorphic granular texture. Their main mineral assemblage includes subhedral to euhedral plagioclase (oligoclase, 60–85 vol. %), anhedral to subhedral K-feldspar (5–20 vol. %), subhedral to anhedral

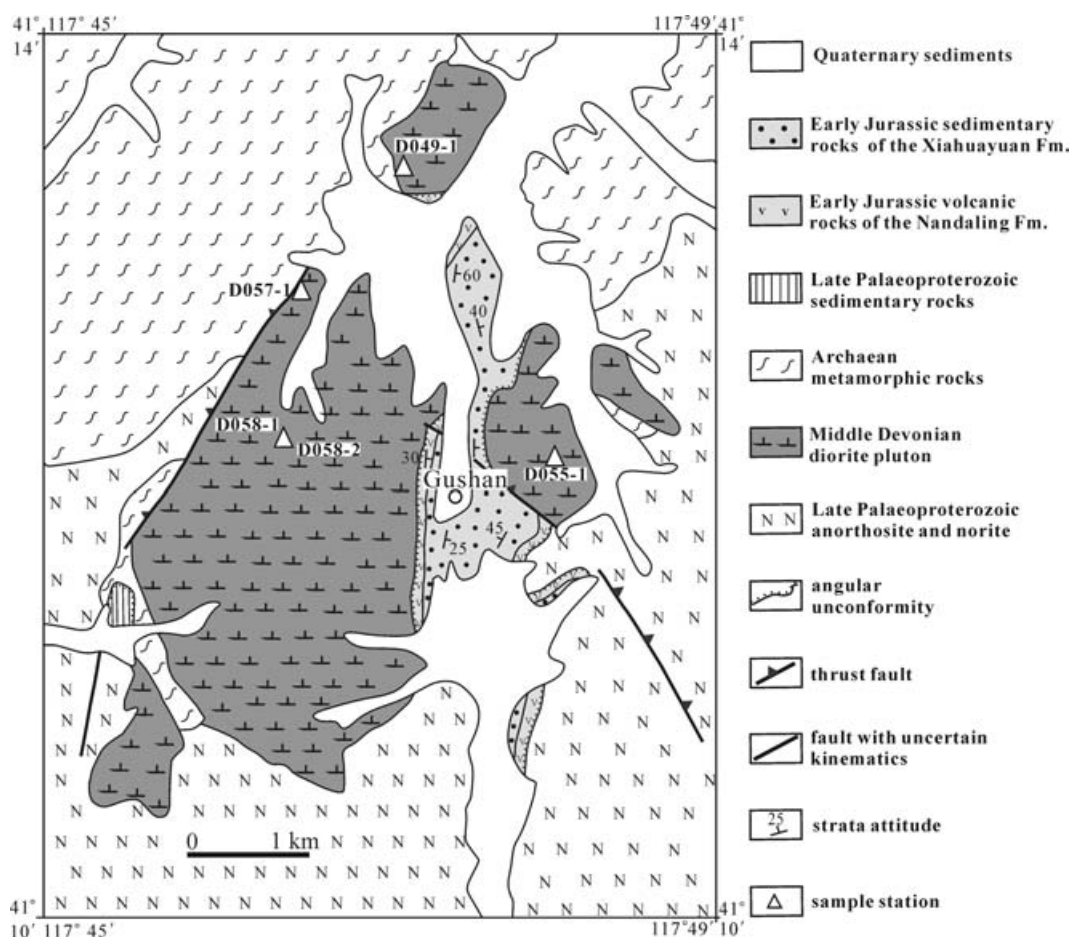


Figure 2. Geological map of the Gushan diorite pluton (modified after Hebei Bureau of Geology and Mineral Resources, 1994).

hornblende (5–15 vol. %), anhedral quartz (0–10 vol. %), anhedral to subhedral biotite (0–3 vol. %) and granular clinopyroxene (0–2 vol. %), and accessory minerals comprise magnetite, titanite, apatite and zircon. The rocks show slight alteration, and secondary minerals include calcite, sericite, chlorite, zoisite, epidote and albite. The quartz monzodiorite displays a transitional relationship with the monzodiorite in the field (Fig. 2).

3.b. Sample description

Five samples were collected from different parts of the Gushan pluton for geochemical analyses (Fig. 2). A representative monzodiorite sample (D055-1) from the middle-west part of the pluton (Fig. 2) was selected

to separate zircon for SHRIMP U–Pb dating and *in situ* Lu–Hf analyses. Zircons are characterized by transparent, euhedral, short pink prisms that are 150 to 500 μm long. Oscillatory zoning is well developed in cathodoluminescence (CL) images, indicating a typically magmatic genesis of the zircon crystals (Fig. 3). Summaries for all geochronological and geochemical samples from the Gushan pluton are listed in Table 1.

4. Methods and analytical procedures

4.a. Electron microprobe analyses

Electron microprobe analyses were carried out with a JEOL JXA-8800R at the Key Laboratory of the

Table 1. Summary of the samples from the Middle Devonian Gushan pluton

Sample no.	Longitude	Latitude	Rock type	Main mineral assemblage	Subordinate minerals	Secondary minerals
D049-1	117°47'09"	41°13'21"	Monzodiorite	Pl + Hbl + Kfs + Cpx	Mt + Zr + Ap + Tnt	Ser + Epi + Cal + Alb
D055-1	117°48'04"	41°12'09"	Quartz monzodiorite	Pl + Hbl + Kfs + Qtz + Cpx	Mt + Zr + Ap + Tnt	Ser + Epi + Zoi + Alb
D057-1	117°46'26"	41°12'47"	Monzodiorite	Pl + Kfs + Hbl + Bt	Mt + Zr + Ap + Tnt	Ser + Epi + Zoi + Alb
D058-1	117°46'21"	41°12'19"	Monzodiorite	Pl + Kfs + Hbl + Qtz + Bt	Mt + Zr + Ap + Tnt	Ser + Epi + Zoi + Chl
D058-2	117°46'21"	41°12'20"	Monzodiorite	Pl + Kfs + Hbl + Qtz + Bt	Mt + Zr + Ap + Tnt	Ser + Epi + Zoi + Chl

Mineral abbreviations: Pl, plagioclase; Bt, biotite; Hbl, hornblende; Kfs, K-feldspar; Qtz, quartz; Cpx, clinopyroxene; Tnt, titanite; Mt, magnetite; Ap, apatite; Zr, zircon; Chl, chlorite; Epi, epidote; Zoi, zoisite; Cal, calcite; Ser, sericite; Alb, albite.

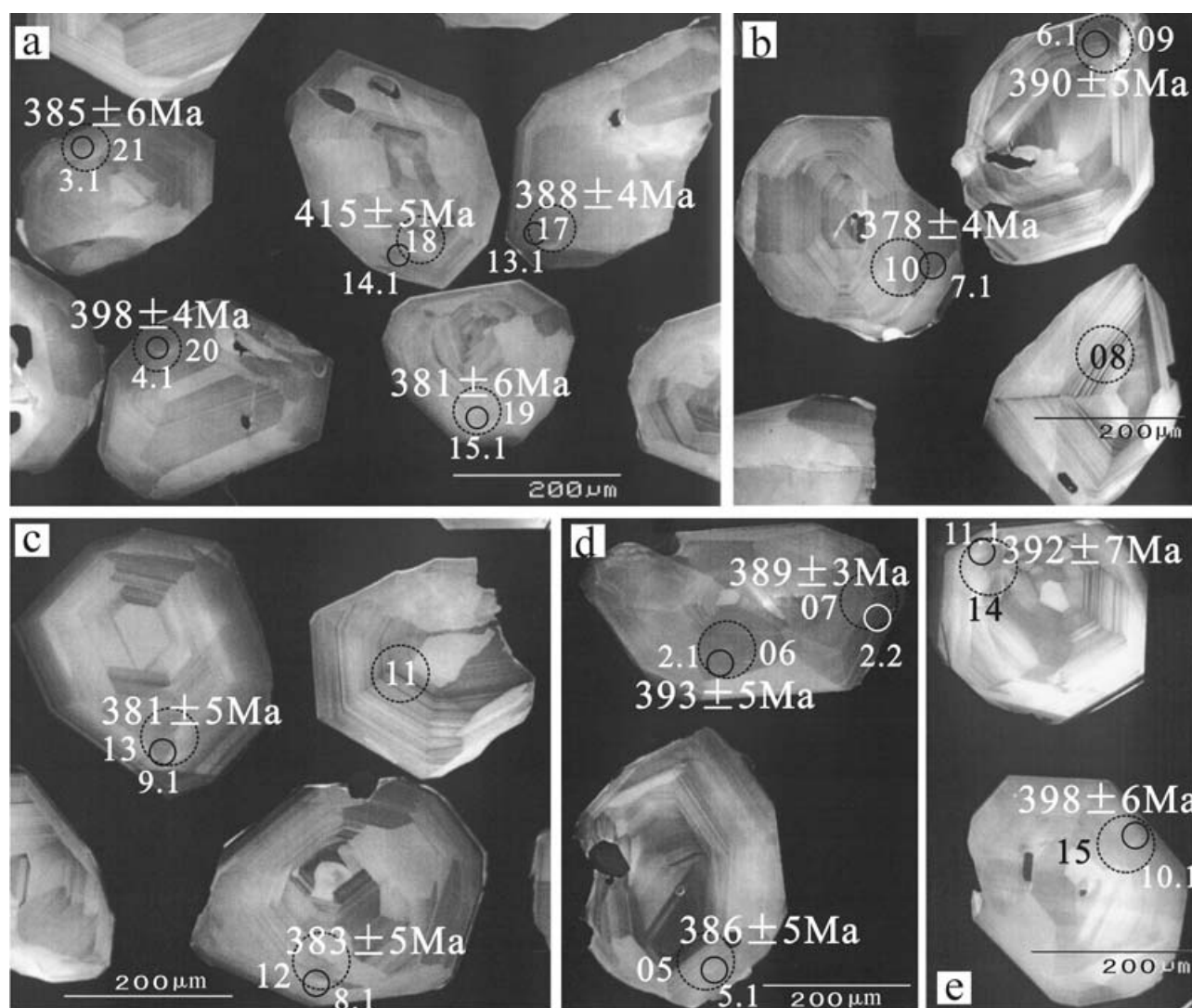


Figure 3. CL image of representative dating spots of zircon SHRIMP U-Pb and *in situ* Lu-Hf analyses from the Gushan pluton. Small circles are zircon SHRIMP U-Pb dating spots, and larger dashed circles are *in situ* Lu-Hf analysis spots.

Institute of Mineral Resources, Chinese Academy of Geological Sciences. Quantitative analyses of rock-forming minerals were performed with a 20 kV accelerating voltage, a 20 nA beam current and a 2–5 μm beam size. The counting time at each peak was 20–30 s.

4.b. SHRIMP zircon U-Pb geochronology

Zircons were extracted using conventional separation techniques and were then handpicked under a binocular microscope. Together with the TEMORA zircon standard they were mounted in epoxy and polished to expose the cores of the grains in CL, SHRIMP U-Pb and *in situ* Lu-Hf analyses. CL images were performed at the Research School of Earth Sciences, Australian National University.

U-Pb dating was performed on the SHRIMP II at the Beijing SHRIMP Centre following the method of

Williams (1998). The mass resolution was about 5000 at 1 % peak height. The spot size of the ion beam was 25–30 μm , and five scans through the mass range were used for data collection. The SL13 (572 Ma, U = 238 ppm) and TEMORA (417 Ma) standards were used in the analyses as discussed by Black *et al.* (2003). Sites for dating were selected on the basis of CL and microscope images. In order to maintain precision, one TEMORA analysis was performed after every three or four spots on the sample zircons during data collection. Ages and concordia diagrams were produced using the programs SQUID 1.03 (Ludwig, 2001) and ISOPLOT/Ex 2.06 (Ludwig, 1999).

4.c. Major and trace element analyses

Major elements except FeO were analysed on fused glass discs by X-ray fluorescence spectrometry (XRF) and FeO contents by classical wet chemical analysis

at the National Geological Analytical Center of China. Trace elements were determined by a Finnigan MAT Element 2 high-resolution ICP-MS at the State Key Laboratory of Mineral Deposits Research, Nanjing University. Details of sample preparation and ICP-MS analytical procedures have been described by Qi, Hu & Gregoire (2000). The Chinese national standard GSR-1 was used to monitor analyses. The analytical uncertainties are estimated as less than 1 % for other major components except 5 % for P_2O_5 , and less than 10 % for all trace elements.

4.d. *In situ* Lu–Hf isotope analyses

In situ Lu–Hf isotope analyses were performed using a Geolas 193 nm laser-ablation microprobe, attached to a Neptune multi-collector ICP-MS at the State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, using techniques described by Griffin *et al.* (2000, 2002). Analyses were carried out with beam diameters of 63 μm , 6 Hz repetition rates, and 30 sec ablation times. For the calculation of initial Hf isotope ratio, the decay constant for ^{176}Lu proposed by Scherer, Munker & Mezger (2001) was used. For the calculation of $\varepsilon_{\text{Hf}}(T)$ values we have adopted the chondritic values of Blichert-Toft & Albarede (1998). Calculated Hf model ages (T_{DM}) are based on the depleted mantle model described by Griffin *et al.* (2000). Because Hf model ages (T_{DM}) can only give a minimum age for the source material of the magma from which the zircon crystallized, we also calculated crustal model ages (T_{DM}^{C}) which assume that the parental magma was produced from an average continental crust ($^{176}\text{Lu}/^{177}\text{Hf} = 0.015$; $f_{\text{Lu/Hf}} = -0.55$; GERM database) that originally was derived from the depleted mantle (Griffin *et al.* 2000).

4.e. Rb–Sr and Sm–Nd isotopic analyses

Samples for Rb–Sr and Sm–Nd isotopic analysis were dissolved in Teflon bombs after being spiked with ^{84}Sr , ^{87}Rb , ^{150}Nd and ^{147}Sm tracers prior to $\text{HF} + \text{HNO}_3$ (with a ratio of 2:1) dissolution. Rb, Sr, Sm and Nd were separated using conventional ion exchange procedures and measured using a Finnigan MAT 262 multi-collector mass spectrometer at the Laboratory for Radiogenic Isotope Geochemistry, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. Procedural blanks were < 100 pg for Sm and Nd and < 500 pg for Rb and Sr. $^{143}\text{Nd}/^{144}\text{Nd}$ were corrected for mass fractionation by normalization to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. Typical within-run precision (2σ) for Sr and Nd was estimated to be ± 0.000015 . The measured values for the Ames Nd standard and the NBS-607 Sr standard were $^{143}\text{Nd}/^{144}\text{Nd} = 0.512132 \pm 15$

and $^{87}\text{Sr}/^{86}\text{Sr} = 0.710257 \pm 12$ during the period of data acquisition, respectively. The USGS standard BCR-2 prepared using the same procedures as the samples yielded $\text{Rb} = 45.94$, $\text{Sr} = 340.9$, $^{87}\text{Rb}/^{86}\text{Sr} = 0.3898$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.704990 \pm 11$ (2σ), $\text{Sm} = 6.536$, $\text{Nd} = 28.14$, $^{147}\text{Sm}/^{144}\text{Nd} = 0.1404$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512625 \pm 10$ (2σ).

5. Results

5.a. Mineral chemistry

The representative analytical data for 11 feldspars and 10 hornblendes from the Gushan pluton are listed in Tables 2 and 3, respectively.

K-feldspar is almost pure orthoclase with very high Or content (> 90 %). Plagioclases exhibit a slightly wider range of compositions and are classified as oligoclase and albite ($\text{Ab} = 70.3\text{--}98.5$).

Generally, hornblendes from individual samples show narrow ranges of composition, and no core–rim zoning was found in individual hornblende grains. According to the nomenclature of Leake *et al.* (1997), the hornblendes are classified as hastingsite, magnesiohastingsite or pargasite and have $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ ratios ranging from 0.40–0.50.

5.b. SHRIMP U–Pb dating results

The SHRIMP U–Pb analysis results of Gushan monzodiorite (sample D055-1) are listed in Table 4 and plotted on a concordia diagram in Figure 4. Sixteen spots from 15 zircon grains were measured, and most of them have concordant ages. The 16 spots yielded a weighted $^{206}\text{Pb}/^{238}\text{U}$ mean age of 390 ± 5 Ma (95 % confidence, $\text{MSWD} = 3.4$). The well-developed oscillatory zones and high Th/U ratios (> 0.25) indicate they are typically magmatic zircons, revealing emplacement of the pluton at 390 ± 5 Ma, namely Middle Devonian times.

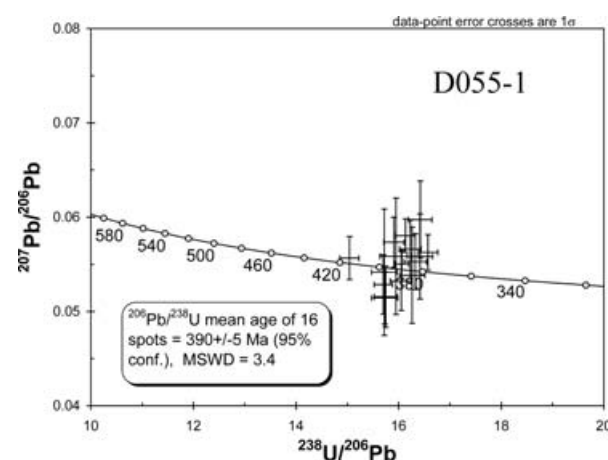


Figure 4. SHRIMP U–Pb concordia diagram for zircons from the Gushan pluton.

Table 2. Representative compositions of feldspar from the Gushan granotoid pluton

Sample Spots	D049-1 1	D049-1 2	D055-1 1	D055-1 2-a	D055-1 2-b	D057-1 1-a	D057-1 1-b	D057-1 2	D058-2 1	D058-2 2	D058-2 3
SiO ₂	67.02	67.27	68.50	64.82	62.18	62.05	67.48	68.27	61.46	61.86	61.06
TiO ₂	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.01	0.02
Al ₂ O ₃	20.14	20.08	19.14	17.66	23.50	24.03	20.01	19.75	23.98	23.75	24.20
FeO	0.01	0.04	0.00	0.03	0.06	0.08	0.08	0.10	0.02	0.07	0.04
MnO	0.00	0.00	0.02	0.00	0.01	0.00	0.03	0.00	0.00	0.00	0.00
MgO	0.01	0.01	0.00	0.01	0.00	0.02	0.01	0.00	0.00	0.00	0.02
CaO	1.28	1.29	0.23	0.02	5.26	5.73	1.19	0.86	5.87	5.77	6.12
Na ₂ O	10.83	10.88	11.57	0.87	8.56	8.30	11.03	11.41	8.27	8.28	8.17
K ₂ O	0.14	0.07	0.07	16.04	0.17	0.13	0.15	0.06	0.12	0.12	0.11
Cr ₂ O ₃	0.04	0.02	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.02	0.02
NiO	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00
Total	99.48	99.66	99.53	99.46	99.77	100.35	99.99	100.46	99.73	99.89	99.76
Cations (O = 8)											
Si	2.954	2.959	3.010	3.028	2.768	2.747	2.965	2.984	2.741	2.755	2.727
Al	1.046	1.040	0.990	0.972	1.232	1.253	1.035	1.016	1.259	1.245	1.273
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
Fe ²⁺	0.000	0.001	0.000	0.001	0.002	0.003	0.003	0.004	0.001	0.003	0.001
Mn	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Mg	0.001	0.001	0.000	0.001	0.000	0.001	0.001	0.000	0.000	0.000	0.001
Ca	0.060	0.061	0.011	0.001	0.251	0.272	0.056	0.040	0.280	0.275	0.293
Na	0.926	0.928	0.986	0.079	0.739	0.713	0.940	0.967	0.715	0.715	0.708
K	0.008	0.004	0.004	0.956	0.010	0.007	0.008	0.003	0.007	0.007	0.006
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ni	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	4.995	4.994	5.002	5.038	5.002	4.996	5.009	5.014	5.003	5.000	5.010
Mol. %											
Ab	93.2	93.5	98.5	7.6	73.9	71.9	93.6	95.7	71.4	71.7	70.3
An	6.0	6.1	1.1	0.1	25.1	27.4	5.6	4.0	27.9	27.6	29.1
Or	0.8	0.4	0.4	92.3	1.0	0.7	0.8	0.3	0.7	0.7	0.6
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Structural formulas for all plagioclases were calculated on the basis of 8 oxygens and 5 cations.

5.c. Major and trace element geochemistry

5.c.1. Major element compositions

All samples from the Gushan pluton are characterized by low content of SiO₂ (53.17 wt %–55.78 wt %) and high content of Al₂O₃ (17.18 wt %–20.53 wt %), Fe₂O₃T (5.80 wt %–9.65 wt %), CaO (6.26 wt %–7.98 wt %), Na₂O (4.44 wt %–5.97 wt %), K₂O + Na₂O (6.77 wt %–8.01 wt %) and high Na₂O/K₂O (1.88–4.70) ratios (Table 5). In the total alkali v. silica (TAS) plot, all samples fall within or near the field of monzodiorite and the alkaline field (Fig. 5). They are metaluminous in terms of their molar ratios of Al₂O₃/(CaO + Na₂O + K₂O) and Al₂O₃/(Na₂O + K₂O). On Harker variation diagrams, TiO₂, Fe₂O₃T, MnO, MgO, CaO and P₂O₅ decrease with increasing of SiO₂, but Na₂O, Al₂O₃ and K₂O increase with increasing of SiO₂ (Fig. 6). The samples display Mg no. values ranging from 29.1 to 36.4 (Table 5) and negative correlations with SiO₂ (Fig. 6).

5.c.2. Rare earth element (REE) compositions

Samples from the Gushan pluton have total REE contents (Σ REE) ranging from 98.9 ppm to 183.9 ppm. On chondrite-normalized REE diagrams (Fig. 7), they

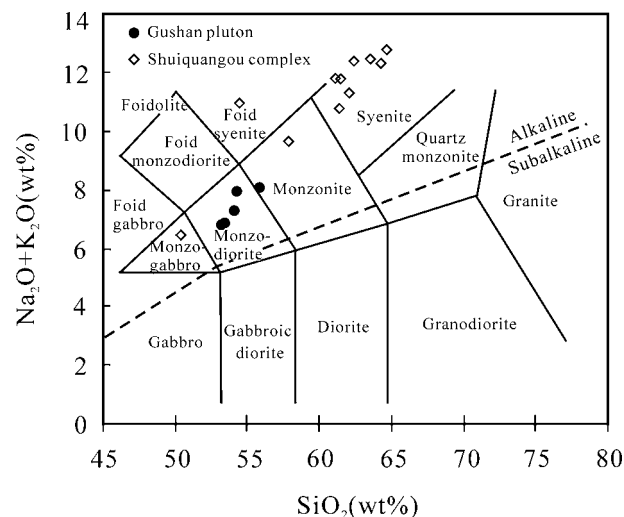


Figure 5. Total alkali v. silica (TAS) plot of the Middle Devonian intrusions. Data from the Shuiquangou complex are from Jiang (2005).

display slight light REE enrichment ($La_N/Yb_N = 9.48$ – 13.83) and basically no to slightly positive Eu anomalies ($Eu_N/Eu_N^* = 1.18$ – 1.50), which are very similar to those of the Shuiquangou syenitic complex (Jiang, 2005).

Table 3. Representative compositions of hornblende from the Gushan granotoid pluton

Sample Spots	D049-1 1	D049-1 2	D055-1 1	D055-1 2-a	D055-1 2-b	D057-1 1	D057-1 2	D058-2 1	D058-2 2	D058-2 3
SiO ₂	40.78	40.59	41.51	41.73	41.73	41.15	41.16	41.23	41.54	41.02
TiO ₂	2.62	2.43	1.98	0.96	2.15	2.47	2.57	2.21	2.26	2.21
Al ₂ O ₃	11.54	11.51	10.73	10.59	10.70	11.71	11.45	11.03	10.71	10.80
FeO	18.21	18.40	19.54	20.31	19.39	17.86	18.14	19.10	18.63	19.06
MnO	0.02	0.51	0.59	0.64	0.55	0.49	0.56	0.53	0.55	0.61
MgO	8.72	8.21	8.14	8.52	8.36	9.31	9.01	8.88	8.88	8.73
CaO	10.77	11.47	10.94	11.24	11.13	11.43	11.31	11.35	11.39	11.28
Na ₂ O	1.63	1.62	1.80	1.94	1.91	1.75	1.68	1.72	1.75	1.76
K ₂ O	1.97	2.12	1.88	1.67	1.97	2.10	2.09	1.92	1.93	1.96
Total	96.26	96.86	97.11	97.60	97.89	98.27	97.97	97.97	97.64	97.43
Formula per Holland & Blundy (1994)										
T site										
Si	6.267	6.259	6.376	6.380	6.367	6.214	6.242	6.269	6.335	6.284
Al ^{IV}	1.733	1.741	1.624	1.620	1.633	1.786	1.758	1.731	1.665	1.716
Total T	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
M1-3 sites										
Al ^{VI}	0.357	0.352	0.319	0.289	0.291	0.299	0.290	0.247	0.261	0.234
Ti	0.303	0.282	0.229	0.110	0.247	0.281	0.293	0.253	0.259	0.255
Fe ³⁺	0.352	0.213	0.345	0.485	0.294	0.325	0.323	0.382	0.300	0.360
Mg	1.997	1.887	1.863	1.941	1.901	2.095	2.036	2.012	2.018	1.993
Mn	0.003	0.067	0.077	0.083	0.071	0.063	0.072	0.068	0.071	0.079
Fe ²⁺	1.989	2.160	2.165	2.092	2.180	1.930	1.977	2.038	2.076	2.080
Ca	0.000	0.040	0.002	0.000	0.016	0.007	0.008	0.000	0.015	0.000
Total M1-3	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
M4 site										
Fe	0.000	0.000	0.000	0.021	0.000	0.000	0.000	0.009	0.000	0.002
Ca	1.773	1.855	1.799	1.841	1.803	1.842	1.830	1.849	1.846	1.851
Na	0.227	0.145	0.201	0.138	0.197	0.158	0.170	0.142	0.154	0.146
Total M4	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
A site										
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Na	0.259	0.340	0.335	0.437	0.368	0.354	0.324	0.365	0.364	0.377
K	0.386	0.417	0.368	0.326	0.383	0.405	0.404	0.372	0.376	0.383
Total A	0.645	0.757	0.703	0.763	0.752	0.759	0.728	0.738	0.739	0.760
Total cat	15.645	15.757	15.703	15.763	15.752	15.759	15.728	15.738	15.739	15.760

Structural formulae for hornblende were calculated on the basis of 23 oxygens following the method outlined in Holland & Blundy (1994).

Table 4. SHRIMP U–Pb dating results of the Gushan monzodiorite (Sample D055-1)

Grain-spot	²⁰⁶ Pb _c (%)	U (ppm)	Th (ppm)	²³² Th/ ²³⁸ U	²⁰⁶ Pb* (ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	²⁰⁷ Pb*/ ²⁰⁶ Pb*	²⁰⁷ Pb*/ ²³⁵ U	²⁰⁶ Pb*/ ²³⁸ U	²⁰⁶ Pb*/ ²³⁸ U Age (Ma)
1.1	0.35	115	40	0.36	6.30	0.00020	0.0514 ± 0.0028	0.451 ± 0.026	0.06360 ± 0.00102	397 ± 6
2.1	0.36	169	85	0.52	9.13	0.00020	0.0573 ± 0.0027	0.497 ± 0.024	0.06286 ± 0.00082	393 ± 5
2.2	0.24	318	78	0.25	17.1	0.00013	0.0550 ± 0.0015	0.473 ± 0.014	0.06227 ± 0.00051	389 ± 3
3.1	1.36	121	34	0.29	6.50	0.00075	0.0538 ± 0.0051	0.456 ± 0.044	0.06148 ± 0.00092	385 ± 6
4.1	0.43	220	90	0.42	12.1	0.00024	0.0529 ± 0.0031	0.464 ± 0.028	0.06369 ± 0.00070	398 ± 4
5.1	0.72	149	77	0.53	7.95	0.00040	0.0566 ± 0.0031	0.481 ± 0.027	0.06163 ± 0.00080	386 ± 5
6.1	0.49	174	55	0.32	9.35	0.00027	0.0532 ± 0.0031	0.457 ± 0.027	0.06230 ± 0.00081	390 ± 5
7.1	0.16	177	66	0.39	9.22	0.00009	0.0563 ± 0.0019	0.468 ± 0.017	0.06034 ± 0.00072	378 ± 4
8.1	0.51	135	48	0.37	7.14	0.00028	0.0553 ± 0.0029	0.467 ± 0.026	0.06125 ± 0.00080	383 ± 5
9.1	0.66	146	51	0.36	7.67	0.00037	0.0597 ± 0.0041	0.502 ± 0.035	0.06089 ± 0.00085	381 ± 5
10.1	1.55	133	71	0.55	7.40	0.00086	0.0542 ± 0.0065	0.475 ± 0.057	0.06360 ± 0.00102	398 ± 6
11.1	1.11	71	19	0.28	3.89	0.00061	0.0559 ± 0.0061	0.483 ± 0.053	0.06270 ± 0.00119	392 ± 7
12.1	1.31	131	41	0.32	7.25	0.00073	0.0516 ± 0.0033	0.451 ± 0.029	0.06351 ± 0.00089	397 ± 5
13.1	0.00	201	50	0.25	10.7	0.00000	0.0580 ± 0.0018	0.496 ± 0.016	0.06199 ± 0.00074	388 ± 4
14.1	0.70	176	55	0.32	10.1	0.00039	0.0557 ± 0.0023	0.510 ± 0.022	0.06648 ± 0.00080	415 ± 5
15.1	0.93	124	42	0.35	6.53	0.00051	0.0558 ± 0.0045	0.469 ± 0.038	0.06091 ± 0.00091	381 ± 6

Note: Errors are 1σ; ²⁰⁶Pb_c (%) indicates the common portions in total ²⁰⁶Pb; ²⁰⁶Pb* refers to the radiogenic ²⁰⁶Pb; Common Pb corrected with ²⁰⁸Pb/²⁰⁶Pb=2.097, ²⁰⁷Pb/²⁰⁶Pb=0.864, ²⁰⁶Pb/²⁰⁴Pb=18.052.

Table 5. Representative major and trace element compositions of the Gushan pluton

Number	D049-1	D055-1	D057-1	D058-1	D058-2
<i>Major element oxides (wt %)</i>					
SiO ₂	54.05	53.42	55.78	53.17	54.29
TiO ₂	0.59	0.99	0.66	0.87	0.80
Al ₂ O ₃	19.46	17.18	20.53	19.48	20.34
Fe ₂ O ₃	5.29	5.68	3.92	4.71	4.41
FeO	1.63	3.57	1.69	2.30	2.18
MnO	0.14	0.26	0.14	0.14	0.14
MgO	1.50	2.50	1.20	2.10	1.57
CaO	7.98	7.59	6.34	7.86	6.26
Na ₂ O	5.97	4.44	5.32	4.68	5.14
K ₂ O	1.27	2.34	2.69	2.09	2.74
P ₂ O ₅	0.33	0.41	0.30	0.40	0.33
LOI	1.55	0.85	0.87	1.90	1.39
Total	99.76	99.23	99.44	99.70	99.59
Fe ₂ O ₃ T	7.10	9.65	5.80	7.27	6.83
A/CNK	0.76	0.73	0.89	0.80	0.89
A/NK	1.74	1.75	1.76	1.96	1.78
Na ₂ O/K ₂ O	4.70	1.90	1.98	2.24	1.88
CaO/Na ₂ O	1.34	1.71	1.19	1.68	1.22
Al ₂ O ₃ /TiO ₂	32.98	17.35	31.11	22.39	25.43
Mg no.	29.5	33.9	29.1	36.4	31.3
<i>Rare earth and trace elements (ppm)</i>					
La	21.79	33.69	25.07	24.76	25.94
Ce	37.41	72.97	47.51	42.55	59.02
Pr	4.75	9.21	6.50	5.45	8.17
Nd	20.31	40.08	27.97	23.15	37.40
Sm	3.80	7.32	4.86	4.06	6.99
Eu	1.49	2.65	2.11	1.92	2.61
Gd	3.35	6.46	4.42	3.77	6.18
Tb	0.47	0.89	0.60	0.50	0.88
Dy	2.42	4.58	3.07	2.57	4.51
Ho	0.45	0.85	0.58	0.48	0.83
Er	1.24	2.39	1.68	1.35	2.25
Tm	0.17	0.32	0.23	0.18	0.29
Yb	1.13	2.18	1.58	1.21	1.85
Lu	0.17	0.32	0.23	0.18	0.26
ΣREE	98.92	183.91	126.42	112.13	157.18
La _N /Yb _N	13.03	10.44	10.72	13.83	9.48
Eu _N /Eu _N *	1.28	1.18	1.39	1.50	1.21
Li	2.25	3.87	12.60	5.86	6.69
Be	1.07	1.25	1.11	0.93	0.98
Sc	5.23	10.29	5.07	8.29	6.45
Co	11.28	15.83	7.62	13.82	11.84
Cu	5.43	14.51	21.10	24.41	22.92
Ga	21.41	21.72	20.85	19.84	20.74
Sn	0.61	1.00	0.83	0.66	0.73
Rb	11.42	30.03	21.86	19.55	25.20
Sr	1817.1	1326.7	1568.5	1559.8	1441.7
Y	11.34	21.30	14.43	12.72	19.40
Zr	43.27	66.58	68.57	48.63	56.18
Nb	2.68	6.56	4.49	3.40	5.52
Ba	355.0	908.1	1527.9	1235.4	1540.5
Hf	1.54	2.62	2.13	1.86	1.93
Ta	0.20	0.40	0.27	0.44	0.62
Pb	5.79	8.54	7.75	6.75	6.14
Th	1.88	3.57	2.09	2.15	2.13
U	0.49	1.28	0.51	0.47	0.45
V	134.12	147.98	84.79	130.58	119.95
Cr	2.69	5.57	4.16	2.61	3.82
Cs	0.19	0.39	0.42	0.34	0.23
Zn	68.14	138.69	97.63	103.64	113.09
Rb/Sr	0.006	0.023	0.014	0.013	0.017
Rb/Ba	0.032	0.033	0.014	0.016	0.016
Rb/Zr	0.264	0.451	0.319	0.402	0.449
Th/Ta	9.40	8.93	7.74	4.89	3.44
Sr/Y	160.20	62.30	108.73	122.66	74.30

Note: Fe₂O₃T, Fe₂O₃ total; LOI, lost on ignition; A/CNK = molecular Al₂O₃/(CaO+Na₂O+K₂O); A/NK = molecular Al₂O₃/(Na₂O+K₂O); Mg no. = molecular FeO/(FeO+MgO); Eu_N, chondrite-normalized Eu; Eu_N* = (Sm_N × Gd_N)^{1/2}.

5.c.3. Trace element compositions

The trace element compositions of the Gushan pluton exhibit constant and low Rb/Sr and Rb/Ba values of 0.006–0.023 and 0.014–0.033, respectively (Table 5). They are characterized by low contents of Y (11.34–21.30), Yb (1.13–2.18) and high Sr/Y (62.3–160.2) ratios. On the primitive mantle-normalized multi-element diagram (Fig. 8), the samples display a strong depletion in Rb, Th, U, Nb, Ta, P, Zr, Hf and Ti and enrichment in Ba, K and Sr, indicating contributions of the ancient crustal materials in their petrogenesis.

5.d. Zircon Hf isotopes and whole rock Sr–Nd isotopes

Zircons from the Gushan monzodiorite show a range of initial ¹⁷⁶Hf/¹⁷⁷Hf ratios from 0.282191 to 0.282366 and ε_{Hf}(T) values from –11.8 to –5.8 (Table 6). The Hf model ages (T_{DM}) for these zircons mainly range between 1.23 and 1.48 Ga. The average crustal model ages (T_{DM}^C) are 1.76–2.14 Ga, much younger than the Hf model ages of Palaeoproterozoic and Archaean intrusions in the North China block (S. H. Zhang, unpub. data; Yang *et al.* 2006).

Two representative Rb–Sr and Sm–Nd isotopic compositions of the Gushan pluton are listed in Table 7. They show a small variation in Sr–Nd isotopic compositions with initial ⁸⁷Sr/⁸⁶Sr ratios from 0.704885 to 0.705053 and ε_{Nd}(T) values from –9.5 to –7.5, respectively. The Nd model ages (T_{DM}) are 1.79–1.88 Ga.

6. Aluminium-in-hornblende barometry and emplacement depth estimate

Aluminium-in-hornblende barometry has been widely used to calculate the pressure and emplacement depth of batholiths (e.g. Ague & Brandon, 1992; Anderson & Smith, 1995; Stein & Dietl, 2001). Most samples from the Gushan pluton contain a mineral assemblage of plagioclase, hornblende, K-feldspar, quartz, biotite, titanite and magnetite, which is suitable for aluminium-in-hornblende barometry (Johnson & Rutherford, 1989; Anderson & Smith, 1995; Stein & Dietl, 2001). The aluminium-in-hornblende barometry calibrated by Anderson & Smith (1995) was used to calculate pressures in this study because of its considerations of the influence of temperature (and oxygen fugacity) on pressure calculations. Pressures were also calculated using the methods of Johnson & Rutherford (1989) and Schmidt (1992) and were compared with results obtained from the Anderson & Smith (1995) calibration.

The temperature-corrected pressures calculated using Anderson & Smith (1995) from the Gushan pluton range from 4.54 to 5.41 kbar (Table 8). These results are very similar to the results of Johnson & Rutherford (1989) but much lower than those of Schmidt (1992)

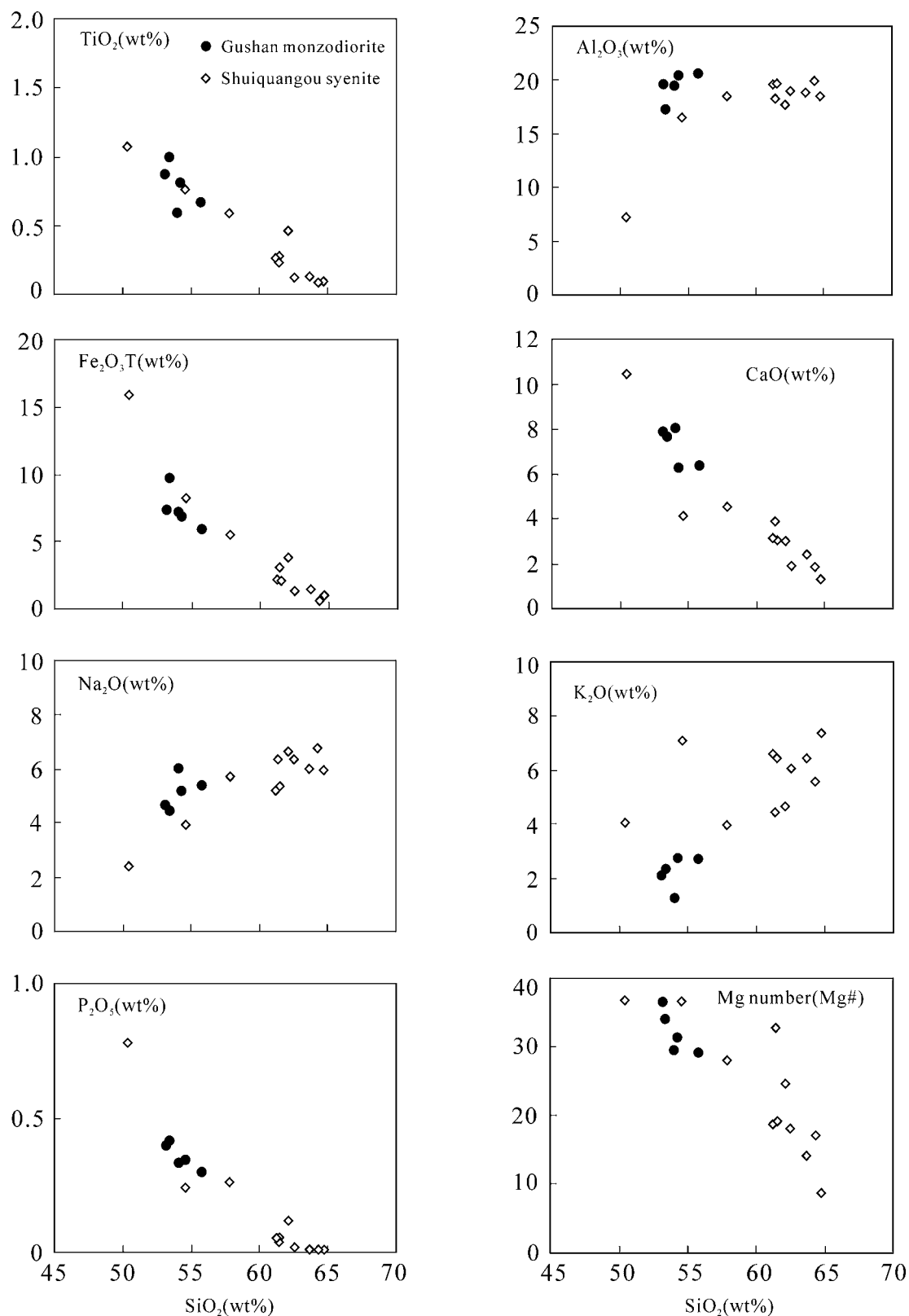


Figure 6. Harker variation diagrams of the Gushan pluton and comparison with the Shuiquangou syenitic complex. Data from the Shuiquangou complex are from Jiang (2005).

(Table 8). The emplacement depth was calculated on the assumption that the average crustal density of the North China block during Middle Devonian times was

2.8 g cm^{-3} . The average palaeodepths of crystallization range from 17.2 to 19.7 km (Table 8). Therefore, the emplacement depth of the Middle Devonian Gushan

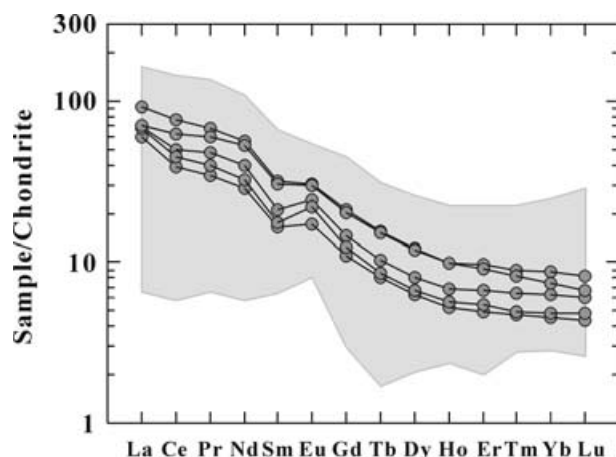


Figure 7. Chondrite-normalized REE patterns of the Gushan pluton and comparison with the Shuiquangou syenitic complex. The chondrite values are from Taylor & McLennan (1985). Data from the Shuiquangou complex (shaded area) are from Jiang (2005).

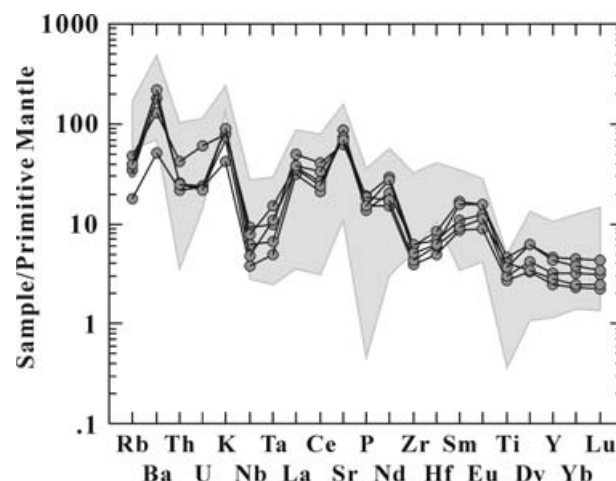


Figure 8. Primitive-mantle-normalized spider diagrams of the Gushan pluton and comparison with the Shuiquangou syenitic complex. Data from the Shuiquangou complex (shaded area) are from Jiang (2005). The primitive mantle values are from Sun & McDonough (1989).

pluton is about 18 km, which is a little larger than that of the Carboniferous plutons (15.7–18.7 km; Zhang, Zhao & Song, 2006).

7. Discussion

7.a. Petrogenesis of the Middle Devonian intrusions

Samples from the Gushan dioritic pluton are characterized by light REE-enrichment, no to slightly positive Eu anomalies, low contents of Y, Yb and high Sr/Y ratio, suggesting a source with residual garnet, amphibole and pyroxene, but little or no olivine

and plagioclase (Stern & Kilian, 1996). On primitive mantle-normalized multi-element diagrams, samples from the Gushan pluton display strong depletion in Rb, Th, U, Nb, Ta, P, Zr, Hf and Ti, and enrichment in Ba, K and Sr, indicating contamination of crustal material in their petrogenesis. Combined with its low SiO₂ content (53.17 wt %–55.78 wt %) and Sr–Nd–Hf isotopic compositions (see following discussions), an enriched mantle origin is proposed for the Gushan diorite pluton. Partial melting of an enriched mantle source can produce melts with very high Sr (and Ba, light REE, etc.), particularly in cases where the degree

Table 6. Hf isotope analyses of zircons from the Gushan monzodiorite (Sample D055-1)

Spots	Age (Ma)	¹⁷⁶ Yb/ ¹⁷⁷ Hf	¹⁷⁶ Lu/ ¹⁷⁷ Hf	¹⁷⁶ Hf/ ¹⁷⁷ Hf	±2σ	ε _{Hf} (0)	ε _{Hf} (T)	T _{DM} (Ma)	T _{DM} ^C (Ma)	Hf _i	f _{Lu/Hf}
01	390	0.022744	0.001269	0.282374	0.000016	−14.07	−5.8	1250	1759	0.282365	−0.96
02	390	0.008831	0.000482	0.282370	0.000016	−14.22	−5.8	1230	1755	0.282366	−0.99
03	390	0.012792	0.000693	0.282317	0.000016	−16.09	−7.7	1311	1876	0.282312	−0.98
04	397	0.012724	0.000643	0.282196	0.000017	−20.37	−11.8	1476	2141	0.282191	−0.98
05	386	0.041556	0.002048	0.282320	0.000019	−15.98	−8.0	1354	1894	0.282305	−0.94
06	393	0.013694	0.000704	0.282230	0.000017	−19.17	−10.7	1432	2068	0.282225	−0.98
07	389	0.005693	0.000332	0.282240	0.000014	−18.81	−10.4	1404	2042	0.282238	−0.99
08	390	0.029006	0.001431	0.282234	0.000021	−19.03	−10.8	1454	2073	0.282224	−0.96
09	390	0.019863	0.000997	0.282370	0.000019	−14.22	−5.9	1247	1763	0.282363	−0.97
10	378	0.013413	0.000661	0.282242	0.000020	−18.74	−10.6	1413	2050	0.282237	−0.98
11	390	0.019552	0.000889	0.282335	0.000021	−15.45	−7.1	1292	1839	0.282329	−0.97
12	383	0.014229	0.000678	0.282227	0.000019	−19.27	−11.0	1435	2080	0.282222	−0.98
13	381	0.015039	0.000682	0.282237	0.000022	−18.92	−10.7	1421	2059	0.282232	−0.98
14	392	0.013056	0.000650	0.282300	0.000019	−16.69	−8.3	1333	1912	0.282295	−0.98
15	398	0.017219	0.000743	0.282217	0.000019	−19.63	−11.1	1451	2095	0.282211	−0.98
16	397	0.006931	0.000322	0.282210	0.000019	−19.87	−11.2	1445	2104	0.282208	−0.99
17	388	0.005094	0.000264	0.282222	0.000019	−19.45	−11.0	1426	2082	0.282220	−0.99
18	415	0.007648	0.000368	0.282240	0.000021	−18.81	−9.8	1405	2028	0.282237	−0.99
19	381	0.008923	0.000433	0.282223	0.000020	−19.42	−11.2	1431	2087	0.282220	−0.99
20	398	0.013302	0.000613	0.282219	0.000019	−19.56	−11.0	1443	2088	0.282214	−0.98
21	385	0.012727	0.000642	0.282248	0.000019	−18.53	−10.2	1404	2032	0.282243	−0.98

Note: ¹⁷⁶Lu decay constant is $1.865 \times 10^{-11} \text{ yr}^{-1}$; chondritic values: ¹⁷⁶Lu/¹⁷⁷Hf = 0.0332 ± 0.0002 , ¹⁷⁶Hf/¹⁷⁷Hf = 0.282772 ± 0.000029 ; Hf_i: initial Hf isotope composition for U–Pb age; $T_{\text{DM}} = 1/\lambda \times \ln\{1 + [({}^{176}\text{Hf}/{}^{177}\text{Hf})_{\text{sample}} - ({}^{176}\text{Hf}/{}^{177}\text{Hf})_{\text{DM}}]/[({}^{176}\text{Lu}/{}^{177}\text{Hf})_{\text{sample}} - ({}^{176}\text{Lu}/{}^{177}\text{Hf})_{\text{DM}}]\}$; $T_{\text{DM}}^{\text{C}} = 1/\lambda \times \ln\{1 + [({}^{176}\text{Hf}/{}^{177}\text{Hf})_{\text{sample,t}} - ({}^{176}\text{Hf}/{}^{177}\text{Hf})_{\text{DM,t}}]/[({}^{176}\text{Lu}/{}^{177}\text{Hf})_{\text{sample}} - ({}^{176}\text{Lu}/{}^{177}\text{Hf})_{\text{DM}}]\} + t$; depleted mantle values: $({}^{176}\text{Lu}/{}^{177}\text{Hf})_{\text{DM}} = 0.0384$, $({}^{176}\text{Hf}/{}^{177}\text{Hf})_{\text{DM}} = 0.28325$; $({}^{176}\text{Lu}/{}^{177}\text{Hf})_{\text{c}} = 0.015$; t = crystallization time of zircon.

Table 7. Rb–Sr and Sm–Nd isotope analyses results of the Gushan diorites

Sample no.	Rb	Sr	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$ (2 σ)	$(^{87}\text{Sr}/^{86}\text{Sr})_i$	Sm	Nd	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$ (2 σ)	$(^{143}\text{Nd}/^{144}\text{Nd})_i$	$\varepsilon_{\text{Nd}}(0)$	$\varepsilon_{\text{Nd}}(\text{T})$	$f_{\text{Sm}/\text{Nd}}$	T_{DM} (Ma)
D055-1	31.67	1312.3	0.0698	0.705273 $\pm$ 12	0.704885	6.691	33.27	0.1216	0.512064 $\pm$ 12	0.511754	–11.2	–7.5	–0.38	1791
D058-1	27.11	1663.2	0.0471	0.705315 $\pm$ 13	0.705053	3.825	19.90	0.1162	0.511944 $\pm$ 11	0.511648	–13.5	–9.5	–0.41	1879

The $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and $\varepsilon_{\text{Nd}}(\text{T})$ values were calculated at $T = 390$ Ma; ^{87}Rb decay constant is $1.42 \times 10^{-11} \text{ yr}^{-1}$; ^{147}Sm decay constant is $6.54 \times 10^{-12} \text{ yr}^{-1}$; The $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{147}\text{Sm}/^{144}\text{Nd}$ ratios of chondrite and depleted mantle at present day are 0.512638 and 0.1967, 0.51315 and 0.2137, respectively.

Table 8. Crystallization pressure and emplacement depth of the Gushan monzodiorite pluton

Sample Spots	D049-1 1	D049-1 2	D055-1 1	D055-1 2-a	D055-1 2-b*	D057-1 1*	D057-1 2	D058-2 1*	D058-2 2*	D058-2 3*
Al_{tot}	2.091	2.093	1.943	1.909	1.925	2.085	2.047	1.977	1.926	1.950
T ($^{\circ}\text{C}$)	759.5	759.5	759.5	759.5	749.6	760.5	759.5	762.4	754.7	770.5
P-Sch (kbar)	6.94	6.95	6.24	6.08	6.15	6.91	6.73	6.40	6.16	6.27
P-A&S (kbar)	5.38	5.39	4.76	4.62	4.68	5.36	5.20	4.90	4.69	4.79
P-J&R (kbar)	5.40	5.41	4.77	4.63	4.91	5.35	5.21	4.85	4.81	4.54
Dp (km)	19.7	19.7	17.4	16.8	17.9	19.5	19.0	17.7	17.5	16.5
Dp _{Aver.} (km)	19.7		17.4		19.3		17.2			

$P(\pm 0.6 \text{ kbar}) = 4.76\text{Al}_{\text{tot}} - 3.01 - \{[T(^{\circ}\text{C}) - 675]/85\} \times \{0.530\text{Al}_{\text{tot}} + 0.005294[T(^{\circ}\text{C}) - 675]\}$ (Anderson & Smith, 1995)

$P(\pm 0.6 \text{ kbar}) = -3.01 + 4.76\text{Al}_{\text{tot}}$ (Schmidt, 1992)

$P(\pm 0.5 \text{ kbar}) = -3.46 + 4.23\text{Al}_{\text{tot}}$ (Johnson & Rutherford, 1989)

Al_{tot} : total aluminium content of hornblende (23 oxygen atoms); T ($^{\circ}\text{C}$): for spots marked with *, T is calculated temperature of co-existing hornblende and plagioclase by Holland & Blundy (1994); for other spots T is the average temperature of the above temperatures; P-Sch: pressure calculated using Schmidt (1992); P-J&R: pressure calculated using Johnson & Rutherford (1989); P-A&S: the temperature-corrected pressure, calculated using Anderson & Smith (1995); Dp: emplacement depth calculated from the temperature-corrected pressure of Anderson & Smith (1995); Dp_{Aver.}: Average emplacement depth.

of partial melting is relatively low (Shand *et al.* 1994; Gibson *et al.* 1995).

The Sr, Nd, Hf isotopic data provide additional constraints on the nature of the source region and petrogenesis of the Gushan pluton. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and $\varepsilon_{\text{Nd}}(\text{T})$ values of the Gushan pluton at 390 Ma range from 0.704885 to 0.705053 and –9.5 to –7.5, respectively, which are very similar to those of the Shuiquangou syenitic complex (initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and $\varepsilon_{\text{Nd}}(\text{T})$ values at 390 Ma are 0.702233–0.70600 and –13.2 to –6.2, respectively; Bao *et al.* 2003; Jiang, 2005). The negative $\varepsilon_{\text{Nd}}(\text{T})$ values and old Nd model ages (T_{DM} , see Table 7) suggest contributions of the ancient crustal materials. On the $\varepsilon_{\text{Hf}}(\text{T})$ v. emplacement age plot (Fig. 9), all samples from the Gushan pluton fall into an area significantly above the *c.* 2.5 Ga (the main continental growth period of the North China block; e.g. Liu *et al.* 2005; Wu *et al.* 2005) evolutionary trend line of ancient crust, indicating that the parental magma likely originated from a hybrid source between younger mantle components and ancient lower crustal materials. On the $(^{87}\text{Sr}/^{86}\text{Sr})_i$ v. $\varepsilon_{\text{Nd}}(\text{T})$ plot, all rocks from the Gushan and Shuiquangou intrusions fall near or below the extension of the mantle array, pointing towards the field for the lower crust (Fig. 10), indicating the magma originated mainly from enriched mantle components and with some involvement of ancient lower crustal materials. The significantly negative zircon $\varepsilon_{\text{Hf}}(\text{T})$ values and old Hf model ages (T_{DM} and T_{DM}^{C} ; see Table 6) of the Gushan diorite also indicate

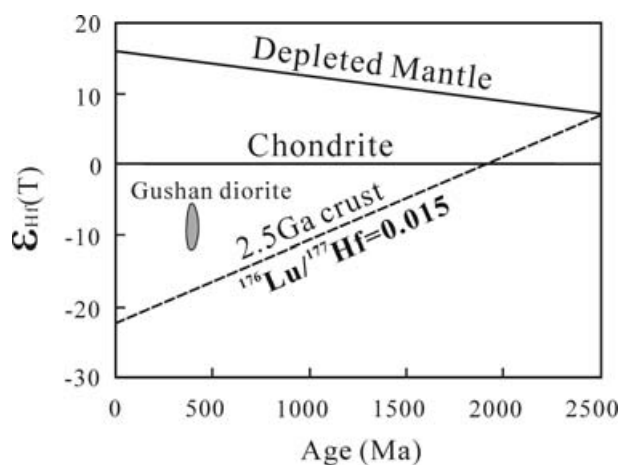


Figure 9. U–Pb age v. initial epsilon Hf for zircons from the Gushan pluton.

that ancient continental crust was involved in magma genesis. On $\varepsilon_{\text{Nd}}(\text{T})$ v. SiO_2 plots, $\varepsilon_{\text{Nd}}(\text{T})$ shows a slight negative correlation with SiO_2 (Fig. 11), indicating some ancient continental crustal contamination during emplacement of the Devonian intrusions. Combined with the major and trace element characteristics, these Middle Devonian intrusions were interpreted as having been produced by re-melting of a type I enriched mantle and involvement of some ancient lower crustal materials during their emplacement.

Although the Gushan pluton displays a distinct lithological assemblage from the Shuiquangou syenitic

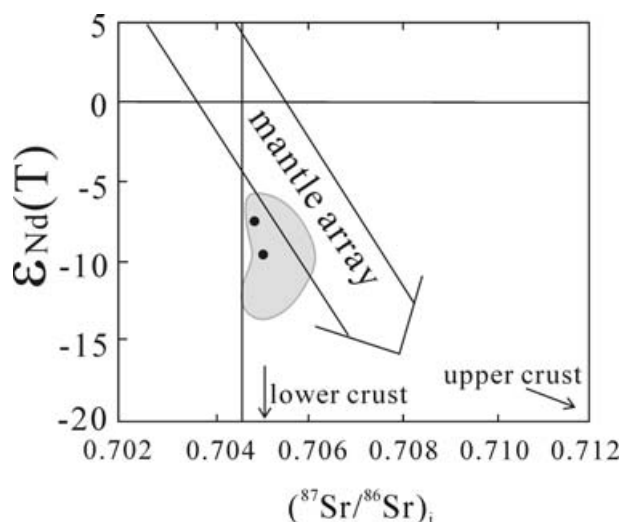


Figure 10. $(^{87}\text{Sr}/^{86}\text{Sr})_i$ v. $\epsilon_{\text{Nd}}(\text{T})$ plot for rocks from the Gushan pluton and comparison with the Shuiquangou syenitic complex. Data from the Shuiquangou complex (shaded area) are from Jiang (2005) and Bao *et al.* (2003).

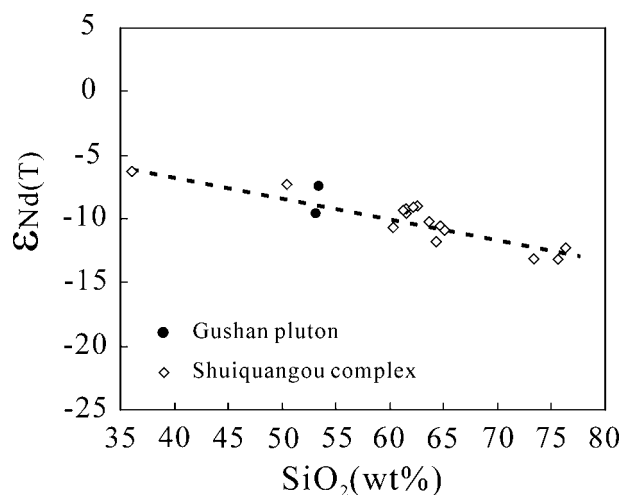


Figure 11. $\epsilon_{\text{Nd}}(\text{T})$ v. SiO_2 plot of the Devonian intrusions. Data from the Shuiquangou complex are from Jiang (2005) and Bao *et al.* (2003).

complex, their geochemical and isotopic compositions are very similar in many aspects (Figs 7, 8, 10), indicating that they may have similar source characteristics and probably co-magmatic evolutionary series. On variation diagrams of major element contents, all samples from the Gushan diorite pluton fall near the trend line of the Shuiquangou syenites and show good correlations between them (Fig. 6). These facts indicate that the Gushan diorite pluton and the Shuiquangou syenitic complex could have originated from a similar parental magma or source region but have undergone different fractional crystallization. However, there are some differences between them. The Shuiquangou complex has higher contents of K and Rb but lower

contents of Ti and Ca than the Gushan pluton (Figs 6, 8). Petrology differences and bulk-rock major and trace element variations of these rocks are probably a result of differential fractional crystallization and crustal contamination processes during emplacements of these intrusions.

7.b. Tectonic setting of the Middle Devonian intrusions

Although the Palaeozoic tectonic history of the northern margin of the North China block is still poorly understood, some studies suggest existence of a Bainaimiao arc during Early Palaeozoic times, and that the Palaeo-Asian oceanic plate was subducted southward (e.g. Wang, 1983; Hu, Xu & Niu, 1990; Xiao *et al.* 2003; Fig. 12). The Bainaimiao arc has been thought to be an island arc (Tang & Yan, 1993) or a magmatic arc at an active continental margin setting (Xiao *et al.* 2003). The ages of the Bainaimiao arc are still poorly constrained, and preliminary geochronology studies on the greenschist and granitoid intrusions from the arc yielded isotopic ages (Rb–Sr, Sm–Nd, U–Pb) widely ranging from 466 Ma to 386 Ma (Wang, 1983; Tang & Yan, 1993). We suggest that the Middle Devonian intrusions on the northern margin of the North China block are likely a product of minor back-arc extension related to southward subduction of the Palaeo-Asian oceanic plate or occurring during the cessation of the subduction (Fig. 12).

7.c. Lithospheric mantle beneath the northern margin of the North China block

Because of the infrequent distribution of the Early Palaeozoic and Devonian magmatic rocks, especially mantle-derived mafic rocks in the North China block, it is still uncertain whether an enriched mantle existed beneath the northern North China block during Palaeozoic times. Geochemical and Sr–Nd–Hf isotopic studies on the Devonian Gushan pluton and comparison with the Shuiquangou syenitic complex suggest that a type I enriched lithosphere mantle existed beneath the northern margin of the North China block during Devonian times. Some Early Palaeozoic kimberlites at Mengyin (perovskite U–Pb age 457 Ma) in western Shandong, and Fuxian (perovskite U–Pb age 463 Ma) in southern Liaoning Province from the eastern North China block (Fig. 1 inset) have initial $^{87}\text{Sr}/^{86}\text{Sr}$ values ranging from 0.70309 to 0.70873 and $\epsilon_{\text{Nd}}(\text{T})$ values from –4.2 to 2.2, respectively (Lu *et al.* 1995; Zheng & Zhao, 1996), indicating that the mantle beneath the North China block was little or not enriched and probably unhomogeneous during Early Palaeozoic times. The enrichment of the lithospheric mantle beneath the northern margin of the North China block was likely related to the southward subduction of the

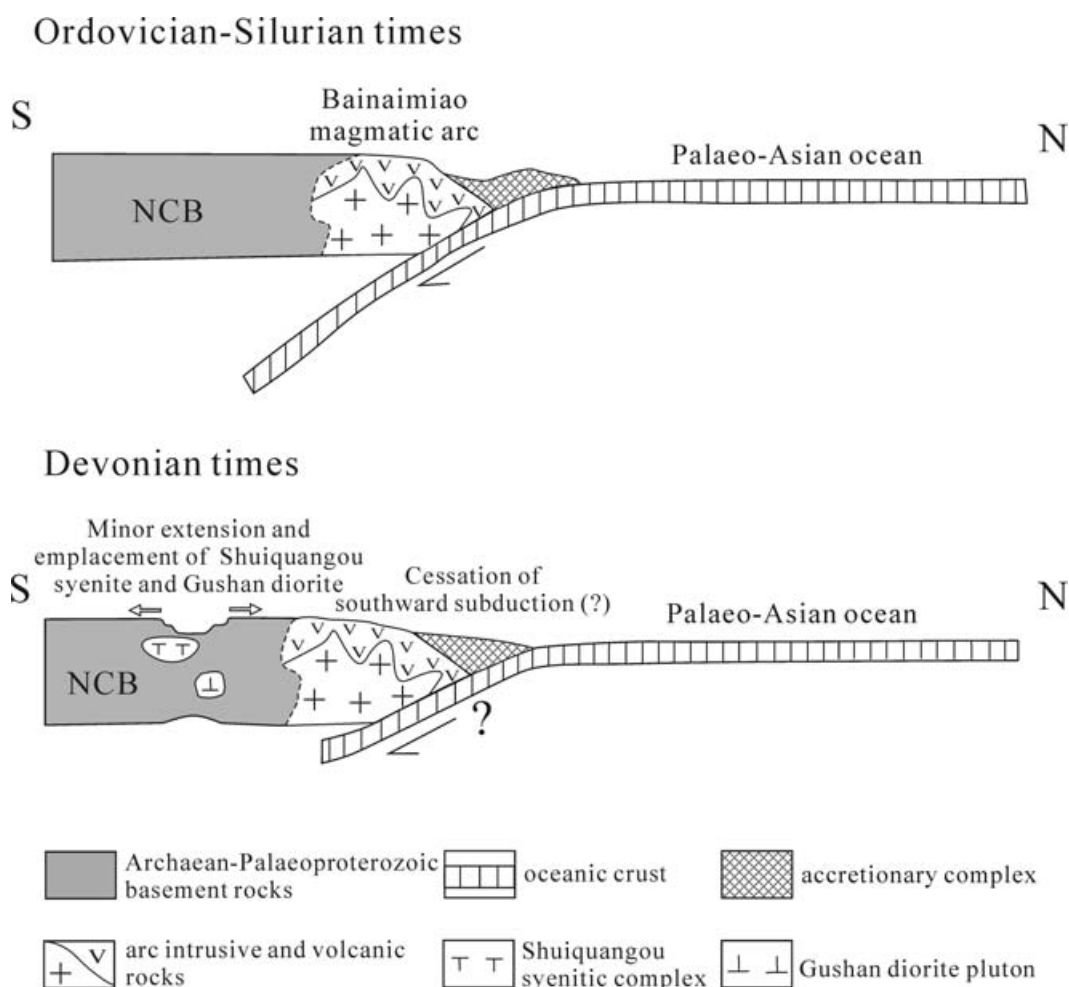


Figure 12. Schematic cartoons demonstrating the tectonic evolution of the northern margin of the North China block (NCB) during Ordovician to Devonian times (modified after Xiao *et al.* 2003) and emplacement of the Middle Devonian intrusions. See text for discussion. Not to scale.

Palaeo-Asian oceanic plate during Early Palaeozoic or early Late Palaeozoic times.

distinct as those during Late Carboniferous to Early Jurassic times (Zhang, Zhao & Song, 2006).

7.d. Emplacement depth of the Gushan pluton and their tectonic implications

The aluminium-in-hornblende barometry calibration after Anderson & Smith (1995) indicates that the emplacement depth of the Gushan pluton was around 18 km. Because it is unconformably overlain by the Lower Jurassic Nandaling Formation and Xiahuayuan Formation (Fig. 2), the Gushan pluton was already exposed at the surface prior to Early Jurassic times. Therefore, the exhumation amplitude of the Gushan pluton was about 18 km during Middle Devonian (*c.* 390 Ma) to Early Jurassic times (*c.* 180 Ma). This emplacement depth is a little larger than, but not significantly different from that of the Carboniferous plutons (15.7–18.7 km; Zhang, Zhao & Song, 2006), indicating that the uplift and exhumation of the plutons in the Inner Mongolia Palaeo-uplift during Middle Devonian to Late Carboniferous times were not as

8. Conclusions

- (1) The Middle Devonian intrusions at the northern margin of the North China block were produced by fractional crystallization of a parental magma derived from partial melting of a type I enriched mantle, with some involvement of ancient lower crustal materials. Their emplacement ages are around 390 Ma.
- (2) The Middle Devonian intrusions were emplaced in a minor back-arc extension environment related to southward subduction of the Palaeo-Asian oceanic plate or during the cessation of the subduction. The emplacement depth of the Gushan diorite pluton is about 18 km.
- (3) Emplacement depth estimates indicate that around 18 km of crustal rocks in the Inner Mongolia Palaeo-uplift were exhumed from Middle Devonian to Early Jurassic times. Combined

with the results from the Carboniferous plutons, the uplift and exhumation of the plutons in the Inner Mongolia Palaeo-uplift during Middle Devonian to Late Carboniferous times were not as distinct as those during Late Carboniferous to Early Jurassic times. The strong uplift and exhumation of the Inner Mongolia Palaeo-uplift were achieved during Late Carboniferous to Early Jurassic times.

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References

- AGUE, J. J. & BRANDON, M. T. 1992. Tilt and northward offset of Cordilleran batholiths resolved using igneous barometry. *Nature* **360**, 146–9.
- ANDERSON, J. L. & SMITH, D. R. 1995. The effects of temperature and fO_2 on the Al-in-hornblende barometer. *American Mineralogist* **80**, 549–59.
- BAO, Z. W., ZHAO, Z. H., ZHANG, P. H. & WANG, Y. X. 2003. REE, Sr, Nd, and Pb isotopic evidences for the petrogenesis of the Shuiquangou syenitic complex of Zhangjiakou. *Geological Review* **49**, 596–604 (in Chinese with English abstract).
- BLACK, L. P., KAMO, S. L., ALLEN, C. M., ALEINIKOFF, J. N., DAVIS, D. W., KORSCH, R. J. & FOUDOUIS, C. 2003. TEMORA 1: A new zircon standard for Phanerozoic U–Pb geochronology. *Chemical Geology* **200**, 155–70.
- BLICHERT-TOFT, J. & ALBAREDE, F. 1998. The Lu–Hf isotope geochemistry of chondrites and the evolution of the mantle-crust system. *Earth and Planetary Science Letters* **148**, 243–58.
- CUI, S. & WU, Z. 1997. On the Mesozoic and Cenozoic intracontinental orogenesis of the Yanshan area, China. In *Proceedings of the 30th International Geological Congress*, vol. 14 (ed. Y. D. Zheng), pp. 277–92. Netherlands: VSP International Science Publishers.
- DAVIS, G. A., ZHENG, Y. D., WANG, C., DARBY, B. J., ZHANG, C. H. & GEHRELS, G. 2001. Mesozoic tectonic evolution of the Yanshan fold and thrust belt, with emphasis on Hebei and Liaoning Provinces, Northern China. In *Paleozoic and Mesozoic tectonic evolution of central Asia: From continental assembly to intracontinental deformation* (eds M. S. Hendrix & G. A. Davis), pp. 171–97. Geological Society of America Memoir no. 194.
- GIBSON, S. A., THOMPSON, R. N., LEONARDOS, O. H., DICKIN, A. P. & MITCHELL, J. G. 1995. The late Cretaceous impact of the Trindade mantle plume: evidence from large-volume, mafic, potassic magmatism in SE Brazil. *Journal of Petrology* **36**, 189–229.
- GRIFFIN, W. L., PEARSON, N. J., BELOUSOVA, E., JACKSON, S. E., VAN ACHTERBERGH, E., O'REILLY, S. Y. & SHEE, S. R. 2000. The Hf isotope composition of cratonic mantle: LAM-MC-ICPMS analysis of zircon megacrysts in kimberlites. *Geochimica et Cosmochimica Acta* **64**, 133–47.
- GRIFFIN, W. L., WANG, X., JACKSON, S. E., PEARSON, S. E., O'REILLY, S. Y., XU, X. S. & ZHOU, X. M. 2002. Zircon Chemistry and Magma Genesis, SE China: *In situ* analysis of Hf isotopes, Tonglu and Pingtan Igneous Complexes. *Lithos* **61**, 237–69.
- HEBEI BUREAU OF GEOLOGY AND MINERAL RESOURCES. 1974. *Geological map of Chengde (Scale 1:200000)*. Shijiazhuang: Hebei Bureau of Geology and Mineral Resources (in Chinese).
- HEBEI BUREAU OF GEOLOGY AND MINERAL RESOURCES. 1989. *Regional geology of Hebei Province, Beijing Municipality and Tianjin Municipality*. Beijing: Geological Publishing House, 741 pp. (in Chinese with English abstract).
- HEBEI BUREAU OF GEOLOGY AND MINERAL RESOURCES. 1994. *Geological map of Hanmaying (Scale 1:50000)*. Shijiazhuang: Hebei Bureau of Geology and Mineral Resources (in Chinese).
- HOLLAND, T. & BLUNDY, J. 1994. Non-ideal interactions in calcic amphiboles and their bearing on amphibole-plagioclase thermometry. *Contributions to Mineralogy and Petrology* **116**, 433–47.
- HONG, D., HUANG, H., XIAO, Y., XU, H. & JIN, M. 1995. Permian alkaline granites in central Inner Mongolia and their geodynamic significance. *Acta Geologica Sinica* **8**, 27–39.
- HU, X., XU, C. & NIU, S. 1990. *Evolution of the Early Palaeozoic continental margin in northern margin of the North China Platform*. Beijing: Peking University Press, 216 pp. (in Chinese with English abstract).
- HUANG, T. K. 1945. *On major tectonic forms of China*. Geological Memoirs of the Geological Survey of China, Series A, no. 20. Chungking: National Geological Survey of China, 165 pp.
- JIANG, N. 2005. Petrology and geochemistry of the Shuiquangou syenitic complex, northern margin of the North China Craton. *Journal of the Geological Society, London* **162**, 203–15.
- JOHNSON, M. C. & RUTHERFORD, M. J. 1989. Experimental calibration of the aluminum-in-hornblende geobarometer with application to Long Valley Caldera (California) volcanic rocks. *Geology* **17**, 837–41.
- KRÖNER, A., WINDLEY, B. F., KHAIN, E. V., JAHN, B. M., HEGNER, E., BADARCH, G., TOMURTOGOO, O., KUZMICHEV, A. & LIU, D. 2004. Accretionary growth and crust-formation in the Central Asian Orogenic Belt during the Neoproterozoic and Palaeozoic and comparison with the present southwest Pacific. In *4-D Framework of the Continental Crust, 2004 International Basement Tectonics Association Conference Program with Abstracts*, pp. 78–80. June 27–July 1, 2004, Oak Ridge, Tennessee, USA.
- LEAKE, B. E., WOOLLEY, A. R., ARPS, C. E. S., BIRCH, W. D., GILBERT, M. C., GRICE, J. D., HAWTHORNE, F. C., KATO, A., KISCH, H. J., KRIVOVICHEV, V. G., LINTHOUT, K., LAIRD, J., MANDARINO, J., MARESCH, W. V., NICKEL, E. H., ROCK, N. M. S., SCHUMACHER, J. C., SMITH, D. C., STEPHENSON, N. C. N., UNGARETTI, L., WHITTAKER, E. J. W. & YOUZHI, G. 1997. Nomenclature of amphiboles: Report of the Subcommittee on Amphiboles

- of the International Mineralogical Association Commission on New Minerals and Mineral Names. *Canadian Mineralogist* **35**, 219–46.
- LIAONING BUREAU OF GEOLOGY AND MINERAL RESOURCES, 1989. *Regional geology of Liaoning Province*. Beijing: Geological Publishing House, 858 pp. (in Chinese with English abstract).
- LIU, S. W., PAN, Y. M., XIE, Q. L., ZHANG, J., LI, Q. G. & YANG, B. 2005. Geochemistry of the Palaeoproterozoic Nanyang granitic gneisses in the Fuping complex: implications for the tectonic evolution of the Central Zone, North China Craton. *Journal of Asian Earth Science* **24**, 643–58.
- LU, F., ZHAO, L., DENG, J. & ZHENG, J. 1995. The discussion on the age of kimberlitic magma activity in North China platform. *Acta Petrologica Sinica* **11**, 365–74 (in Chinese with English abstract).
- LUDWIG, K. R. 1999. *User's Manual for Isoplot/Ex, version 2.06: A geochronological toolkit for Microsoft Excel*. Berkeley Geochronology Center, Special Publication no. 1a, 49 pp.
- LUDWIG, K. R. 2001. *SQUID 1.02: A user's manual*. Berkeley Geochronology Center, Special Publication no. 2, 19 pp.
- LUO, Z. K., MIAO, L. C., GUAN, K., QIU, Y. S., QIU, Y. M., MCNAUGHTON, N. J. & GROVES, D. I. 2001. SHRIMP chronological study of the Shuiquangou intrusive body in Zhangjiakou area, Hebei Province and geochemical significance. *Geochimica* **30**, 116–22 (in Chinese with English abstract).
- PAN, Y. 1996. Early Permian Bajiazi ultra-unit intrusive rock and its emplacement mechanism, Jianping area. *Liaoning Geology* 284–92 (in Chinese with English abstract).
- QI, L., HU, J. & GREGOIRE, D. C. 2000. Determination of trace elements in granites by inductively coupled plasma mass spectrometry. *Talanta* **51**, 507–13.
- REN, J., CHEN, T., NIU, B., LIU, Z. & LIU, F. 1990. *Tectonic evolution of the continental lithosphere and metallogeny in Eastern China and adjacent area*. Beijing: Science Press, 194 pp. (in Chinese).
- SCHERER, E., MUNKER, C. & MEZGER, K. 2001. Calibration of the lutetium-hafnium clock. *Science* **293**, 683–7.
- SCHMIDT, M. W. 1992. Amphibole composition in tonalite as a function of pressure: An experimental calibration of the Al-in-hornblende barometer. *Contributions to Mineralogy and Petrology* **110**, 304–10.
- SHAND, P., GASKARTH, J. W., THIRLWALL, M. F. & ROCK, N. M. 1994. Late Caledonian lamprophyre dyke swarms of South-Eastern Scotland. *Mineralogy and Petrology* **51**, 277–98.
- SONG, H. 1999. Characteristics of Yanshan type intraplate orogenic belts and a discussion on its dynamics. *Earth Science Frontiers* **6**, 309–16 (in Chinese with English abstract).
- STEIN, E. & DIETL, C. 2001. Hornblende thermobarometry of granitoids from the Central Odenwald (Germany) and their implications for the geotectonic development of the Odenwald. *Mineralogy and Petrology* **72**, 185–207.
- STERN, C. R. & KILIAN, R. 1996. Role of the subducted slab, mantle wedge and continental crust in the generation of adakites from the Andean Austral Volcanic Zone. *Contributions to Mineralogy and Petrology* **123**, 263–81.
- SUN, S. S. & MCDONOUGH, W. F. 1989. Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. In *Magmatism in the Ocean Basins* (eds A. D. Saunders & M. J. Norry), pp. 313–45. Geological Society of London, Special Publication no. 42.
- TANG, K. & YAN, Z. 1993. Regional metamorphism and tectonic evolution of the Inner Mongolia suture zone. *Journal of Metamorphic Geology* **11**, 511–22.
- TAYLOR, S. R. & MCLENNAN, S. M. 1985. *The Continental Crust: Its Composition and Evolution*. Oxford: Blackwell Scientific Publications, 312 pp.
- WANG, D. F. 1983. Geochemistry and isotopic dating of the Palaeozoic Bainaimiao island arc system in the Inner Mongolia. In *Contributions to the Project of Plate Tectonics in the Northern China No. 1* (ed. K. D. Tang), pp. 186–208. Beijing: Geological Publishing House (in Chinese with English abstract).
- WANG, Y. 1996. *Tectonic evolutionary processes of Inner Mongolia-Yanshan orogenic belt in eastern China during the Late Palaeozoic-Mesozoic*. Beijing: Geological Publishing House, 142 pp. (in Chinese with English abstract).
- WILDE, S. A., ZHAO, G. C. & SUN, M. 2002. Development of the North China Craton during the late Archaean and its final amalgamation at 1.8 Ga; some speculations on its position within a global Palaeoproterozoic supercontinent. *Gondwana Research* **5**, 85–94.
- WILLIAMS, I. S. 1998. U–Th–Pb geochronology by ion microprobe. In *Applications of microanalytical techniques to understanding mineralizing processes* (eds M. A. McKibben, W. C. Shanks III & W. I. Ridley), pp. 1–35. *Reviews in Economic Geology* **7**.
- WU, F. Y., ZHAO, G. C., WILDE, S. A. & SUN, D. Y. 2005. Nd isotopic constraints on crustal formation in the North China Craton. *Journal of Asian Earth Science* **24**, 523–45.
- XIAO, W., WINDLEY, B. F., HAO, J. & ZHAI, M. G. 2003. Accretion leading to collision and the Permian Solonker suture, Inner Mongolia, China: Termination of the central Asian orogenic belt. *Tectonics* **22**, 1484–505.
- XIE, G. H. 1980. Petrochemical characteristics of the anorthosite suite in Damiao, Hebei Province, China. *Geochimica* **9**, 263–77 (in Chinese with English abstract).
- YANG, J. H., WU, F. Y., SHAO, J. A., XIE, L. W. & LIU, X. M. 2006. In-situ U–Pb dating and Hf isotopic analyses of zircons from volcanic rocks of the Houcheng and Zhangjiakou Formations in the Zhang-Xuan area, northeast China. *Earth Science* **31**, 71–80 (in Chinese with English abstract).
- ZHANG, S. H., ZHAO, Y. & SONG, B. 2006. Hornblende thermobarometry of the Carboniferous granitoids from the Inner Mongolia Palaeo-uplift: Implications for the geotectonic evolution of the northern margin of North China block. *Mineralogy and Petrology* **87**, 123–41.
- ZHANG, S. H., ZHAO, Y., SONG, B. & WU, H. 2004a. The Late Palaeozoic gneissic granodiorite pluton in early Precambrian high-grade metamorphic terrains near Longhua County in northern Hebei Province, North China: result from zircon SHRIMP U–Pb dating and its tectonic implications. *Acta Petrologica Sinica* **20**, 621–6 (in Chinese with English abstract).
- ZHANG, S. H., ZHAO, Y., SONG, B., YANG, Z. Y., HU, J. M. & WU, H. 2007. Carboniferous granitic plutons from the northern margin of the North China block: Implications for a Late Palaeozoic active continental margin. *Journal of the Geological Society, London* **164**, 51–63.

- ZHANG, Y., WU, F., WILDE, S. A., ZHAI, M., LU, X. & SUN, D. 2004b. Zircon U–Pb ages and tectonic implications of ‘Early Palaeozoic’ granitoids at Yanbian, Jilin Province, northeast China. *Island Arc* **13**, 484–505.
- ZHAO, G. C., WILDE, S. A., CAWOOD, P. A. & SUN, M. 2001. Archaean blocks and their boundaries in the North China Craton: Lithological, geochemical, structural and P–T path constraints and tectonic evolution. *Precambrian Research* **107**, 45–73.
- ZHENG, J. P. & ZHAO, L. 1996. Geochemistry of kimberlite from North China craton. In *Kimberlite from North China craton and lithosphere mantle* (eds J. S. Chi & F. X. Lu), pp. 133–78. Beijing: Science Press (in Chinese).