

Geochemistry of Mesozoic mafic volcanic rocks from the Yanshan belt in the northern margin of the North China Block: relations with post-collisional lithospheric extension

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Abstract: Major element, trace element and Sr–Nd isotope data for three suites of mafic volcanic rocks that erupted at c. 180 Ma (Group 1), c. 163–140 Ma (Group 2) and 136–110 Ma (Group 3) in the Yanshan belt in the northern margin of the North China Block (NCB) are presented in this paper. All the rocks show significant enrichment in large ion lithophile elements and light REE (LREE) but depletion in Nb–Ta and Th–U, and moderately radiogenic Sr ($^{87}\text{Sr}/^{86}\text{Sr}(i) = 0.7052\text{--}0.7068$) and unradiogenic Nd ($\epsilon_{\text{Nd}}(t) = -15.1$ to -7.2) isotopic compositions. Sr–Nd isotopic modelling suggests an insignificant role of crustal contamination or assimilation fractional crystallization, and the geochemical variations in these rocks were mainly attributed to source heterogeneity and variable degrees of ferromagnesian, plagioclase and accessory mineral fractionation. The low Th/La (0.039–0.10) points to recycling of low-Th/La (e.g. Th/La < 0.2) ancient crustal materials into the source region, probably related to the palaeo-Asian Ocean subduction. Compared with the late Mesozoic mafic rocks from the NCB interior, the Yanshan belt mafic lavas generally have higher Al_2O_3 , TiO_2 , P_2O_5 , LREE, high field strength elements, Sr and $^{87}\text{Sr}/^{86}\text{Sr}(i)$ but lower MgO and compatible elements. Major element extrapolation (MgO = 8% normalization) reveals that the Yanshan belt mafic volcanic rocks have higher Ti_8 and Fe_8 , and lower Si_8 than those from the NCB interior, suggesting that they were probably derived from a relatively fertile mantle source, different from the Mesozoic chemically refractory lithospheric mantle beneath the NCB interior. Combining the geochemical features of the mafic rocks with Mesozoic deformation events in the northern NCB, we suggest that the three stages of mafic volcanism were caused by episodic lithospheric extension. The Group 1 rocks, which occur locally along major faults, were generated during a post-compressional extension related to the collision between the NCB and Mongolian Block; the Group 2 rocks formed as a result of post-collisional lithospheric extension related to the collision between the North China–Mongolian Block and the Siberian plate; and the Group 3 rocks were extruded in an extensional regime in response to lateral escape related to surrounding plate interactions.

Mafic magmatism in orogenic belts provides important information on mantle–crust interaction, and chemical–thermal evolution of the lithosphere beneath plate margins (e.g. Menzies & Kyle 1990). The origin of such melts is commonly attributed to lithospheric extension by orogenic collapse (e.g. Ruppel 1995), slab breakoff (Davies & Brandenburg 1995), convective thinning (England & Houseman 1989) or delamination of continental lithosphere (Bird 1979; Kay *et al.* 1993). Unlike intraplate basalts (e.g. continental flood basalts, ocean island basalts (OIB) and mid-ocean ridge basalts (MORB), etc.), which usually show MORB- or OIB-type geochemical characters, most orogenic mafic magmas exhibit arc-like trace element features (high large ion lithophile element to high field strength element ratios (LILE/HFSE) and light rare earth element (LREE)/HFSE values) and enriched isotopic signatures inherited from previous subduction-related enrichment (e.g. Hawkesworth *et al.* 1995; Turner *et al.* 1996; Jahn *et al.* 1999;

Miller *et al.* 1999; Fan *et al.* 2003, 2004; Guo *et al.* 2004). However, orogenic magmas are mainly derived from lithospheric mantle instead of a convective mantle wedge above a subducted slab (e.g. Hawkesworth *et al.* 1995; Turner *et al.* 1996; Fan *et al.* 2003). The geochemical features of these mafic rocks provide important constraints on geodynamic processes in lithospheric evolution.

The North China Block (NCB) is known as one of the oldest continental blocks of the Earth, with crustal ages as old as c. 3.8 Ga (Liu *et al.* 1992). It is surrounded by the Triassic Qinling–Dabie–Sulu collisional orogen to the south and the late Palaeozoic to early Mesozoic NE China Fold Belt to the north (Fig. 1). The Yanshan belt is located between the NCB interior and the NE China Fold Belt (Fig. 1a; Sengor & Natal'in 1996; Davis *et al.* 2001). In the Mesozoic, episodic magmatism occurred coupled with multistage crust–lithosphere deformation events. The frequent tectono-magmatic events in this area have attracted the

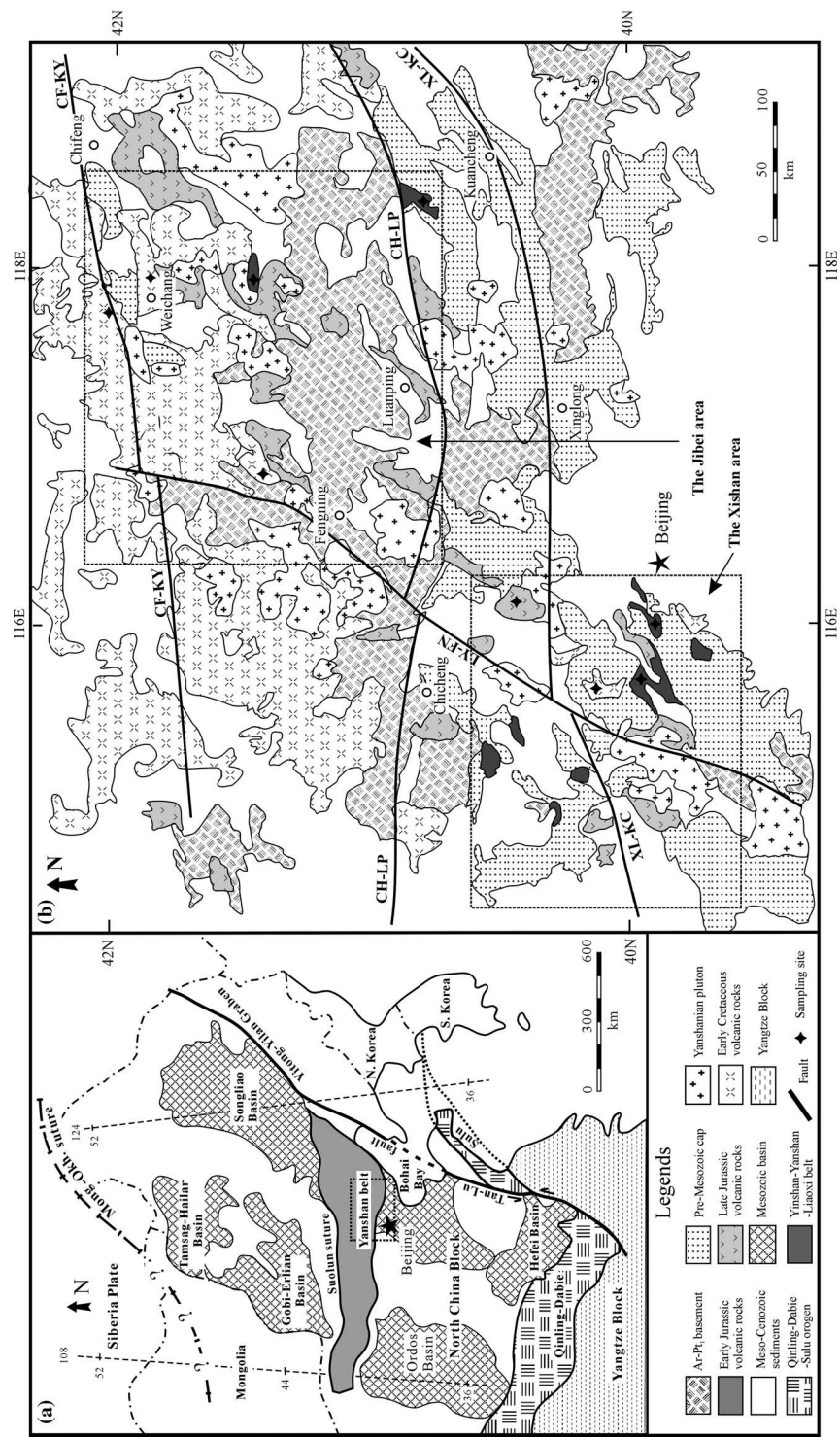


Fig. 1. (a) A simplified map showing the major tectonic units of the North China Block and its surrounding areas (modified from Davis *et al.* 2001). (b) A geological map showing the distribution of Mesozoic volcanic rocks in the Yanshan belt of the northern North China Block. CF-KY, Chifeng–Kaiyuan fault; CH-LP, Chicheng–Luanping fault; XL-KC, Xinglong–Kuancheng fault; LY-FN, Laiyuan–Fengning fault.

interest of international geologists, and many hypotheses for their origin have been proposed; for example, the 'Yanshan Movement' (Wong 1929), intracontinental or intraplate orogeny (e.g. Zhang & Song 1997; Chen 1998; Zheng *et al.* 2000; Davis *et al.* 2001), and an active continental margin of the palaeo-Pacific Ocean (e.g. Deng *et al.* 1999; Faure & Natal'in 1992). To date, the major controversies on the Mesozoic lithospheric evolution are: (1) the role of the palaeo-Pacific plate in the accretion of the East Asian continental margin; (2) the relative contributions of the Mesozoic collision between the North China–Mongolian Block and the Siberian plate, and the collision between the North China and Yangtze Blocks; (3) the effect of plate interactions in the formation of the NE–SW trending structural lineation since the late Mesozoic.

Although some studies are concerned with the Mesozoic magma origin in the northern NCB (e.g. Li *et al.* 2001; Shao *et al.* 2001; Zhou *et al.* 2001; Zhang *et al.* 2003), the nature of the subcontinental lithospheric mantle (SCLM), the relationship between structural deformation and magmatism, and the causes for the frequent tectonomagmatic events are still poorly understood. To further explore the geodynamics of Mesozoic tectono-magmatism in the Yanshan belt, we report here major element, trace element and Sr–Nd isotope data for three groups of Mesozoic mafic volcanic rocks, which were extruded in the early and late Jurassic, and the early Cretaceous. The purposes of this study are to: (1) constrain the nature of the Mesozoic SCLM beneath the northern NCB; (2) understand the genesis of these Mesozoic mafic rocks; (3) discuss the possible mechanisms for melt generation and its relationship with crust–lithosphere deformation.

Regional geology

The Yanshan belt is the eastern segment of the east–west-trending Yinshan–Yanshan orogen in the northern NCB. The regional geology has been widely covered in previous studies (e.g. Bao *et al.* 1995; Zhai *et al.* 1996; Wu *et al.* 2000; Zhang & Song 1997; Davis *et al.* 2001; Shao *et al.* 2001; Cui *et al.* 2002; Liu *et al.* 2002). The Archaean to early Proterozoic was the most important crustal growth stage (e.g. Liu *et al.* 1992; Zhai *et al.* 1996). High-grade metamorphic terranes are widely exposed, intruded by widespread hypersthene granites and tonalite–trondhjemite–granites (TTG) of 2.4–2.5 Ga (e.g. Zhai *et al.* 1996). At *c.* 1.8 Ga, collision between the western and eastern blocks formed a north–south-trending high-pressure granulite belt (e.g. Zhao *et al.* 2000). The Archaean to

early Proterozoic evolution resulted in the framework of the metamorphic basement.

The Mesoproterozoic Yan–Liao passive rift is characterized by carbonates and terrestrial debris tens of kilometres thick (HBGMR 1989). The rift was closed by the end of the Mesoproterozoic. From the Neoproterozoic to early Palaeozoic, the Yanshan region became a passive continental margin of the palaeo-Asian Ocean, on which kilometre-scale neritic carbonates were deposited. Similar to the NCB interior, a stratigraphic gap from the Upper Ordovician to Lower Carboniferous marks uplift of the continent. During late Palaeozoic time, there developed a series of east–west-trending basins related to the closure of the palaeo-Asian Ocean, which contain predominant terrestrial deposits and extensive coal layers, and minor littoral sediments. The emplacement of the Indo-Sinian alkaline complexes may signify the termination of orogeny related to the palaeo-Asian Ocean (e.g. Yan *et al.* 2000).

From early Mesozoic time, the Yanshan belt was remobilized and experienced many tectonomagmatic events associated with intracontinental deformation, thrust faults and folds, large-scale nappes and strike-slip faults, and metamorphic core complexes were well developed along this belt (e.g. Davis *et al.* 1998, 2001; He *et al.* 1998; Zheng *et al.* 2000; Wu *et al.* 2000). Subsequently, extensive volcanism, granitoid emplacement and terrestrial deposition took place. Pre-180 Ma south-vergent thrust faulting was prevalent in the northern NCB (e.g. Davis *et al.* 2001), followed by eruption of the Nandaling Formation (FM.) basalts. The second contractional deformation event took place at *c.* 175–163 Ma, at approximately by the time when the North China–Mongolian Block collided with the Siberian plate (e.g. Zhao *et al.* 1990; Davis *et al.* 2001). By the end of the Jurassic, there was an angular unconformity between the Zhangjiakou–Donglingtai and Houcheng–Tuchengzi Fms. In the early Cretaceous, regional deformation was dominated by extension, associated with extensive volcanism and formation of NE–SW trending fault-rift basins. Figure 2 summarizes the Mesozoic volcano-sedimentary history of the Yanshan belt.

Petrography of Mesozoic mafic volcanic rocks

Early Jurassic volcanic rocks (Group 1) are locally distributed along major faults; for example, the Xinglong–Kuancheng fault (also termed the Gubeikou–Pingquan fault; Davis *et al.* 2001) and the Chicheng–Luanping fault (Fig. 1b). The volcanic rocks, which mainly occur in the Xishan area near Beijing city and at the southern margin of the

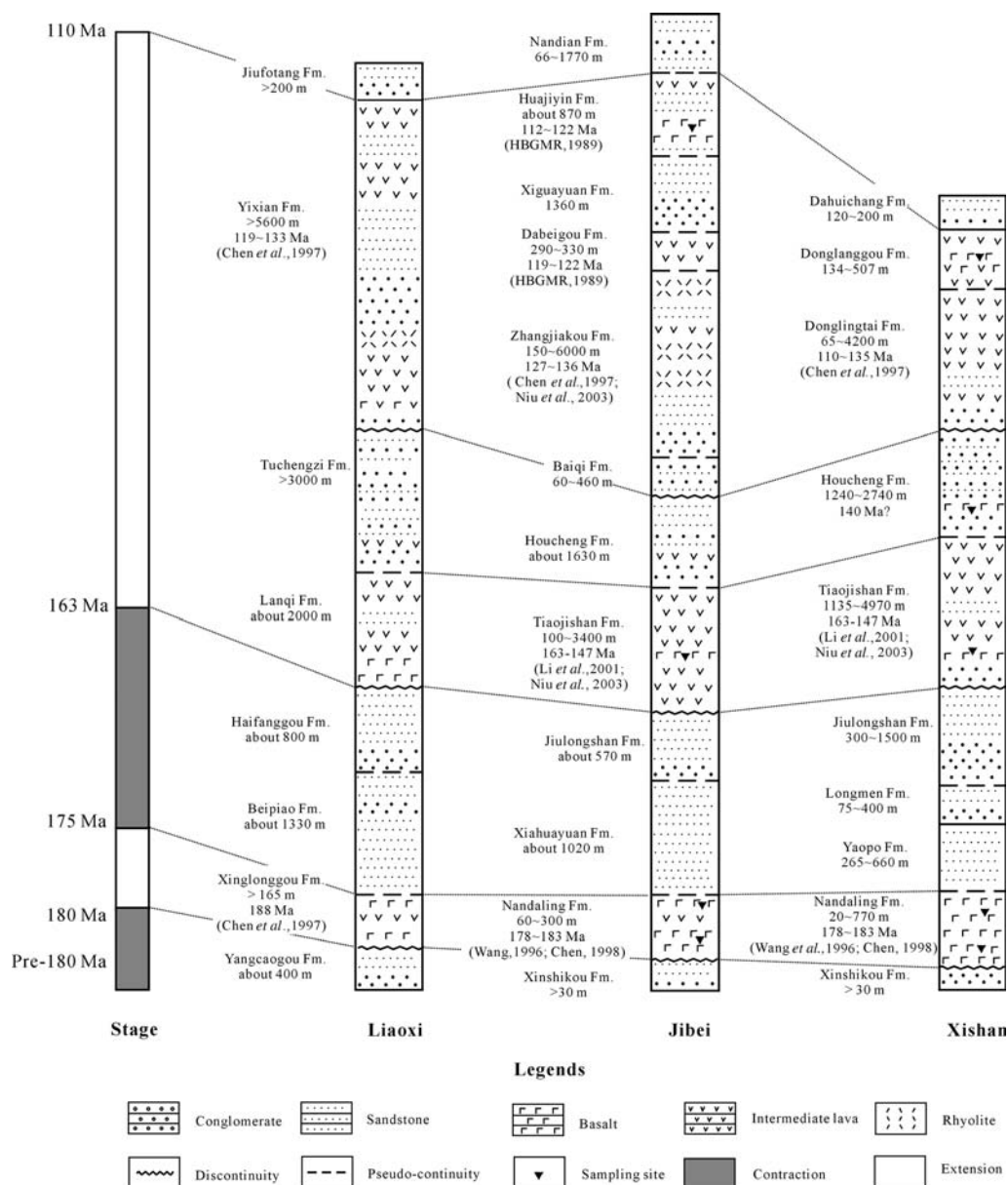


Fig. 2. A schematic summary of the Mesozoic volcano-sedimentary stratigraphic column for the Yanshan belt. The stratigraphic column for the Xishan area is compiled after BBGMR (1991), that for the Jibei area is after HBGMR (1989), and that for the Liaoxi area is after Chen *et al.* (1997). (See details in the text.)

Luanping basin in the Jibei region (Fig. 1b), crop out as subparallel layers or interbeds within the Lower Jurassic Nandaling Fm. The extrusive lavas truncate Upper Triassic shales, sandstones and conglomerates of the Xingshikou Fm., and are underlain unconformably by the Middle Jurassic Yaopo or Xiahuayuan Fm. They consist of basalts, basaltic

andesites and minor andesites that have K–Ar and Ar–Ar whole-rock eruption ages of 178–183 Ma (HBGMR 1989; Wang 1996; Chen 1998; Davis *et al.* 2001). Samples for this study were collected from the Xishan (20XSH-40 to -62) and Jibei (98LP-2 to -12) areas (Fig. 1b). The basalts are weakly porphyritic with predominant

phenocrysts of pyroxene and plagioclase, and minor olivine. The groundmass comprises fine-grained to aphanitic clinopyroxene and plagioclase, with minor ilmenite and other opaque oxides. Weak chloritization has occurred in basaltic samples, as reflected by their Na_2O variation from 2.74 to 5.52% (Table 1). The basaltic andesites are also weakly porphyritic to aphanitic, with predominant clinopyroxene and plagioclase phenocrysts and subordinate amphibole. The matrix is mainly composed of fine-grained or aphanitic clinopyroxene and plagioclase (<0.2 mm), with minor opaque oxides. These rocks have also experienced slight alteration.

The Group 2 rocks are widespread and comprise mainly intermediate–felsic volcanic rocks and minor basaltic lavas. The samples studied here were collected from the Tiaojishan and Houcheng Fms. Volcanic rocks from the Tiaojishan Fm. were erupted at 163–147 Ma (Davis *et al.* 2001; Li *et al.* 2001; Niu *et al.* 2003). The basaltic lavas comprise mainly basaltic andesites and occur as interbeds in the intermediate–felsic rocks. The basaltic andesites are weakly porphyritic to aphanitic, with predominant clinopyroxene and plagioclase phenocrysts and subordinate amphibole, and show weak alteration. The matrix is mainly composed of fine-grained or aphanitic clinopyroxene and plagioclase (<0.2 mm), with minor opaque oxides. The Houcheng Fm. overlies the Tiaojishan Fm., and is overlain by rhyolites of the Zhangjiakou Fm., which has an oldest age of c. 136 Ma (Niu *et al.* 2003). The basaltic lavas that crop out as interbeds in syndepositional conglomerates are fairly fresh, subaphyric to weakly porphyritic, with predominant phenocrysts of clinopyroxene with rare olivine and plagioclase.

The Group 3 lavas were extruded at the time of maximum volcanism in the early Cretaceous. They comprise predominant intermediate–felsic lavas and subordinate basalts, with an age range from 136 to 110 Ma (e.g. HBGM 1989; Chen *et al.* 1997; Davis *et al.* 2001; Niu *et al.* 2003). The intermediate–felsic sequences in the Xishan and Jibei areas are termed the Donglintai and Zhangjiakou Fms., and the basaltic lavas are termed the Donglanggou and Huajiying Fms. (Fig. 2). The samples studied here were collected from both areas, and consist of trachybasalts and basaltic trachyandesites. The trachybasalts are porphyritic with predominant phenocrysts of pyroxene and plagioclase, with minor amphibole and rare olivine. The groundmass is composed of fine-grained clinopyroxene and plagioclase (<0.5 mm). The basaltic trachyandesites are weakly porphyritic with minor clinopyroxene, plagioclase and amphibole phenocrysts, and the matrix is composed of aphanitic materials and minor opaque oxides. Weak chloritization and

kaolinization are prevalent in both trachybasalts and basaltic trachyandesites.

Analytical techniques

All samples were crushed to millimetre size after removal of weathered rims, and fresh chips were handpicked under a binocular microscope. The fresh chips were cleaned in an ultrasonic bath with deionized water. These chips were then crushed to <20 mesh in a WC jaw crusher. A split was ground to <160 mesh grain size in an agate ring mill for major and trace element analysis. Major elements were analysed at the Hubei Institute of Geology and Mineral Resource, Chinese Ministry of Land and Resources (MLR) by wavelength-dispersive X-ray fluorescence spectrometry (XRF) with analytical errors less than 2%. FeO content was analysed by a wet chemical method. The analysed standards have been reported by Fan *et al.* (2004). Trace element abundances of the samples were determined by inductively coupled plasma mass spectrometry (ICP-MS) at the Institute of Geochemistry, Chinese Academy of Sciences (CAS). The powders (about 100 mg) were placed in a screw-top PTFE-lined stainless steel bomb and dissolved by HF and HNO_3 . The sealed bombs were placed in an electric oven and heated to 190 °C for 12 h. Before ICP-MS analysis, 1 ppm Rh solution was added as an internal standard. The analytical errors are estimated to be less than 5% for most elements >10 ppm and about 10% for transition metals such as Cr, Ni, V and Sc, from repetitive analyses of the international standards BHVO-1 (basalt) and AMH-1 (andesite). Duplicate runs gave $<5\%$ RSD (relative standard deviation) for most analysed elements, except for transition metals, which generally gave $<10\%$ RSD. A detailed description of the analytical technique has been reported by Qi *et al.* (2000), and the analytical results for the standards BHVO-1 and AMH-1 are listed in Table 3.

Sr and Nd isotopic ratios were determined by multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) at Guangzhou Institute of Geochemistry, CAS. The Sr and Nd isotopic ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively. Ten analyses of the La Jolla standard gave $^{143}\text{Nd}/^{144}\text{Nd} = 0.511862 \pm 10$, and 12 analyses of BCR-1 gave $^{143}\text{Nd}/^{144}\text{Nd} = 0.512626 \pm 9$. Seven analyses of NBS 987 yielded $^{87}\text{Sr}/^{86}\text{Sr} = 0.710265 \pm 12$. Total procedure blanks were about $2\text{--}5 \times 10^{-10}$ g for Sr and less than 5×10^{-11} g for Nd. $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{147}\text{Sm}/^{144}\text{Nd}$ ratios were calculated using Rb, Sr, Sm and Nd concentrations determined by ICP-MS. $^{87}\text{Sr}/^{86}\text{Sr}(i)$ and $\epsilon_{\text{Nd}}(t)$ for the early

Table 1. Major (in wt%) and trace element (in ppm) compositions of representative Group 1 mafic volcanic rocks from the Yanshan belt

Sample:	20XSH-40	20XSH-41	20XSH-42	20XSH-43	20XSH-44	98LP-2	98LP-4	98LP-8	98LP-12	20XSH-52	20XSH-57	20XSH-58	20XSH-59	20XSH-62
Location:	Xishan	Xishan	Xishan	Xishan	Xishan	Jibei	Jibei	Jibei	Jibei	Xishan	Xishan	Xishan	Xishan	Xishan
Rock type:	HTP-B	HTP-B	HTP-B	HTP-B	HTP-B	LTP-BA	LTP-BA	LTP-BA	LTP-BA	LTP-BA	LTP-BA	LTP-BA	LTP-BA	LTP-BA
SiO ₂	49.24	49.24	48.33	48.40	47.64	53.52	54.07	52.98	52.33	54.06	55.73	53.99	52.41	51.68
TiO ₂	1.92	2.11	2.08	2.14	2.03	1.00	1.15	0.70	0.72	1.10	0.96	1.04	1.24	1.18
Al ₂ O ₃	15.58	15.37	17.61	16.48	16.98	18.9	18.02	19.37	19.13	17.52	15.75	16.26	16.84	17.28
Fe ₂ O ₃	3.01	1.88	7.71	6.49	3.96	2.61	3.45	6.13	6.72	4.01	3.44	3.50	3.67	3.50
FeO	7.22	8.00	3.47	5.70	6.85	4.49	4.15	1.97	0.18	3.30	3.87	3.97	4.47	4.67
MnO	0.15	0.16	0.16	0.16	0.16	0.12	0.11	0.08	0.11	0.09	0.06	0.13	0.08	0.12
MgO	5.62	6.44	3.51	4.71	5.17	3.10	3.80	2.40	3.40	4.63	3.96	4.18	5.75	4.33
CaO	7.73	6.44	6.36	5.11	6.28	4.80	7.10	4.50	4.75	3.31	4.09	4.33	2.73	8.22
Na ₂ O	3.11	3.82	3.47	4.14	4.12	4.23	3.10	5.07	5.43	6.05	5.52	4.54	4.29	2.74
K ₂ O	1.63	1.47	2.75	1.57	1.51	1.11	0.67	1.08	1.11	1.69	1.91	2.86	2.60	2.69
P ₂ O ₅	0.76	0.81	0.77	0.81	0.81	0.60	0.77	0.60	0.64	0.36	0.37	0.38	0.49	0.34
LOI	3.64	3.88	3.35	3.92	4.13	4.70	3.10	3.98	5.00	3.54	4.01	4.38	5.09	2.87
Total	99.61	99.62	99.57	99.63	99.64	99.40	99.89	99.31	99.82	99.66	99.67	99.56	99.66	99.62
Sc	24	25	25	25	24	14	15	14	13	17	17	17	17	23
V	200	202	156	177	174	115	142	148	113	159	161	168	167	226
Cr	113	119	107	119	132	39	76	47	49	40	80	81	16	70
Co	39	35	34	47	39	26	27	23	19	25	23	25	24	26
Ni	61	52	52	71	70	25	30	32	27	22	27	27	12	26
Ba	978	1390	1585	950	932	2039	2540	730	900	1171	972	2113	1376	1212
Rb	24.1	19.9	46.6	26.8	22.1	14.9	5.8	22.9	10.9	31.9	28.5	77.9	49.7	52.3

Sr	1243	541	1173	702	966	1313	1400	998	988	750	708	958	668	999
Th	2.30	2.40	2.54	2.70	2.49	3.41	2.61	3.50	3.67	2.44	2.87	3.05	2.65	2.06
U	0.67	0.64	0.71	0.70	0.59	0.83	0.58	0.89	1.18	0.51	0.61	0.66	0.74	0.49
Zr	274	286	294	310	290	215	202	226	220	155	165	170	198	121
Hf	6.43	6.96	7.23	7.60	6.73	5.10	5.20	5.40	5.13	4.23	4.39	4.48	5.46	3.65
Nb	17.2	18.7	18.4	19.8	18.3	9.3	9.3	9.9	9.9	7.8	9.5	9.8	10.6	6.5
Ta	0.78	0.91	0.91	0.96	0.84	0.47	0.53	0.53	0.57	0.36	0.41	0.42	0.48	0.30
Y	35.7	38.5	35.2	39.3	38.1	18.0	18.5	18.8	18.2	16.0	15.8	16.1	25.9	18.3
La	46.85	49.08	50.48	54.54	50.54	42.47	39.80	45.44	43.91	33.28	37.24	38.68	34.01	23.42
Ce	104.5	109.1	106.4	118.5	109.9	91.3	84.3	96.7	93.1	70.0	76.7	80.2	80.1	52.9
Pr	12.36	12.49	12.85	14.09	13.16	10.73	9.69	11.45	10.41	8.24	8.93	9.24	10.28	6.62
Nd	51.81	52.16	51.26	57.78	55.35	43.49	39.74	45.70	42.40	34.37	34.81	35.97	42.99	28.05
Sm	9.40	9.84	9.22	10.77	10.61	7.97	7.79	8.08	7.87	6.16	6.02	6.19	8.08	5.56
Eu	2.64	2.47	2.58	2.83	2.72	1.95	1.86	2.05	2.04	1.66	1.58	1.69	2.09	1.65
Gd	8.15	8.43	7.91	8.95	8.79	5.84	5.21	5.74	5.63	4.50	4.47	4.71	6.60	4.41
Tb	1.21	1.27	1.21	1.32	1.24	0.78	0.74	0.77	0.72	0.59	0.59	0.59	0.84	0.65
Dy	6.57	7.27	6.65	7.53	7.06	3.67	3.69	3.94	3.87	3.17	2.82	3.03	4.86	3.54
Ho	1.27	1.35	1.26	1.46	1.35	0.70	0.70	0.76	0.70	0.51	0.51	0.53	0.91	0.65
Er	3.45	3.80	3.69	3.92	3.66	1.92	1.98	1.87	1.88	1.41	1.45	1.51	2.35	1.85
Tm	0.51	0.56	0.54	0.57	0.52	0.25	0.23	0.24	0.26	0.20	0.20	0.21	0.34	0.25
Yb	3.21	3.38	3.22	3.62	3.34	1.51	1.67	1.69	1.48	1.17	1.26	1.31	2.10	1.62
Lu	0.44	0.48	0.44	0.54	0.44	0.23	0.27	0.21	0.20	0.18	0.16	0.17	0.29	0.22

HTP: high-Ti-P series; LTP: low-Ti-P series; B, basalt; BA, basaltic andesite.

Table 2. Major (in wt%) and trace element (in ppm) compositions of representative Group 2 mafic volcanic rocks from the Yanshan belt

Sample Location	20XSH-12220XSH-12320XSH-12520XSH-13020XSH-13220XSH-13398LP-2498LP-2698LP-2720XSH-6820XSH-7620XSH-7720XSH-8520XSH-88													
	Xishan TB-H	Xishan TB-H	Xishan TB-H	Xishan TB-H	Xishan TBA-H	Xishan TBA-H	Jibei BA-T	Jibei BA-T	Jibei A-T	Xishan BA-T	Xishan BA-T	Xishan A-T	Xishan A-T	Xishan A-T
Rock type*														
SiO ₂	49.34	49.36	49.75	50.91	51.88	51.39	53.27	55.12	56.03	51.25	52.28	56.97	57.43	56.99
TiO ₂	1.79	1.80	1.76	1.90	1.87	1.68	1.15	1.00	1.05	1.02	1.13	1.10	0.88	1.03
Al ₂ O ₃	17.34	17.27	17.19	15.50	15.35	15.01	19.13	19.06	18.02	19.96	17.61	16.77	15.34	15.41
Fe ₂ O ₃	9.09	6.22	9.13	8.90	8.14	8.25	5.81	5.91	6.06	3.68	5.69	5.45	2.86	5.44
FeO	1.75	3.33	1.83	1.47	1.73	1.90	2.09	0.99	1.24	4.93	1.27	1.47	3.85	1.93
MnO	0.18	0.18	0.15	0.10	0.11	0.13	0.09	0.09	0.13	0.10	0.13	0.09	0.07	0.08
MgO	3.04	4.45	3.42	3.79	3.00	4.06	2.70	2.30	2.50	3.29	3.23	3.51	3.60	3.90
CaO	6.54	6.44	5.90	6.79	6.57	6.15	4.80	4.60	4.90	5.55	7.65	4.04	6.22	5.81
Na ₂ O	4.31	3.86	4.58	3.63	4.22	3.98	4.38	4.66	4.15	4.20	4.48	5.58	3.26	4.16
K ₂ O	2.70	2.95	2.74	2.60	2.97	3.13	2.44	2.22	2.48	2.00	1.69	1.50	2.63	1.73
P ₂ O ₅	0.82	0.84	0.82	0.99	0.96	0.91	0.70	0.93	0.86	0.44	0.5	0.48	0.32	0.33
LOI	2.53	2.80	2.38	2.78	2.75	2.94	3.00	2.70	2.10	3.17	3.95	2.67	3.17	2.83
Total	99.43	99.50	99.51	99.50	99.55	99.53	99.56	99.58	99.52	99.59	99.61	99.63	99.63	99.64
Sc	22	21	22	20	19	18	11	12	11	12	14	13	15	15
V	270	249	259	185	218	155	139	152	138	165	157	132	147	166
Cr	13	12	14	99	98	115	50	51	37	23	51	47	42	18
Co	33	32	32	30	27	32	92	43	22	23	23	22	20	22
Ni	14	14	15	42	39	55	26	27	24	14	23	20	15	18
Ba	2033	1846	1611	1923	1581	1649	1268	1248	1312	1482	1175	1073	1115	1204
Rb	43.2	53.3	48.1	48.1	58.0	61.9	42.7	40.4	44.6	26.8	27.3	28.8	69.0	28.5
Sr	1929	1557	1862	1454	1361	1345	1012	972	845	1242	1408	1263	1138	970
Th	3.68	3.69	3.67	3.87	3.70	3.68	1.54	1.50	1.50	2.25	1.45	1.41	3.37	2.46
U	0.73	0.72	0.80	0.81	0.78	0.73	0.43	0.53	0.44	0.55	0.50	0.56	0.72	0.45

Zr	267	260	265	349	370	355	376	186	183	180	172	162	153	154	150
Hf	6.45	6.23	6.43	8.02	8.53	8.15	8.65	4.57	4.69	4.71	5.30	4.34	4.22	4.33	3.78
Nb	20.9	21.0	21.0	25.1	27.0	25.8	25.0	7.6	7.6	7.7	8.6	8.2	8.0	8.4	7.9
Ta	0.97	0.95	0.95	1.03	1.14	1.06	1.04	0.43	0.38	0.36	0.35	0.32	0.33	0.54	0.34
Y	29.1	28.2	28.9	27.7	29.0	27.9	27.0	13.5	14.0	13.1	17.9	14.8	13.7	15.3	14.8
La	54.88	55.58	55.49	77.05	80.14	78.17	80.40	33.17	33.53	32.39	34.67	35.40	33.85	33.75	30.52
Ce	121.6	119.8	120.4	159.0	167.5	162.7	163.9	74.80	74.64	73.23	75.23	76.75	74.70	69.29	65.18
Pr	14.33	14.22	14.24	18.42	19.44	18.57	18.63	9.06	9.17	9.03	9.02	9.48	9.10	7.94	7.83
Nd	57.11	57.47	56.56	71.70	74.73	72.31	71.04	39.05	39.76	37.77	36.10	38.96	37.22	31.18	31.17
Sm	9.76	10.06	10.12	11.55	12.22	11.83	11.63	7.72	7.64	7.18	6.50	6.91	6.59	5.54	5.49
Eu	2.64	2.60	2.64	2.75	2.79	2.90	2.68	1.92	1.93	1.78	1.75	1.89	1.78	1.45	1.49
Gd	7.81	7.62	7.53	8.22	8.80	8.43	7.99	5.10	5.26	4.59	4.95	4.97	4.60	4.12	4.15
Tb	1.06	1.06	1.01	1.07	1.12	1.09	1.09	0.62	0.65	0.59	0.60	0.59	0.56	0.54	0.55
Dy	5.56	5.38	5.37	5.38	5.86	5.37	5.15	3.28	3.13	2.86	3.21	2.88	2.74	2.86	2.83
Ho	1.01	1.02	1.03	0.94	1.03	0.99	0.93	0.51	0.48	0.46	0.58	0.47	0.44	0.54	0.49
Er	2.64	2.66	2.78	2.61	2.79	2.69	2.50	1.38	1.35	1.21	1.57	1.32	1.17	1.37	1.33
Tm	0.39	0.40	0.39	0.35	0.36	0.38	0.35	0.15	0.13	0.15	0.23	0.17	0.15	0.20	0.19
Yb	2.39	2.42	2.38	2.12	2.23	2.30	2.12	1.01	1.09	0.99	1.41	1.04	1.00	1.32	1.19
Lu	0.35	0.32	0.33	0.31	0.29	0.29	0.30	0.13	0.14	0.15	0.19	0.14	0.13	0.19	0.16

TB, trachybasalt; BTA, basaltic trachyandesite; A, andesite; H, Houcheng Fm.; T, Tiaoqishan Fm.

Table 3. Major (in wt%) and trace element (in ppm) compositions of representative Group 3 mafic volcanic rocks from the Yanshan belt

Sample: Location:	98WC-15		98WC-16		98WC-19		98WC-20		98FN-14		98FN-18		98FN-20		20XSH-29		20XSH-30		20XSH-31		20XSH-32		20XSH-33		AMH-1 This work (n = 6) andesite	BHVO-1 This work (n = 15) basalt	
	Jibei	BTA-H	Jibei	BTA-H	Jibei	BTA-H	TB-H	Jibei	TB-H	Jibei	BTA-H	Jibei	BTA-H	Jibei	TB-H	Xishan	TA-D	Xishan	BTA-D	Xishan	TB-D	Xishan	BTA-D	Xishan	BTA-D		
Rock type:	BTA-H	BTA-H	BTA-H	BTA-H	BTA-H	BTA-H	TB-H	BTA-H	TB-H	Jibei	BTA-H	Jibei	BTA-H	Jibei	TB-H	Xishan	TB-D	Xishan	BTA-D	Xishan	TB-D	Xishan	BTA-D	Xishan	BTA-D		
SiO ₂	52.57	51.76	51.97	49.41	50.87	53.54	54.00	49.59	53.72	48.36	54.55	53.47															
TiO ₂	2.00	1.85	2.00	1.85	2.20	1.38	1.37	1.86	1.54	1.99	1.60	1.60															
Al ₂ O ₃	16.53	19.73	17.01	18.66	17.48	18.10	17.71	15.94	15.45	15.79	15.66	15.73															
Fe ₂ O ₃	3.59	2.92	3.53	3.05	4.41	2.90	3.98	4.63	5.28	4.48	6.10	6.41															
FeO	5.71	5.38	5.47	5.25	5.69	5.2	5.02	4.33	2.32	4.22	1.73	1.93															
MnO	0.14	0.13	0.09	0.14	0.14	0.14	0.15	0.17	0.11	0.19	0.06	0.07															
MgO	3.20	2.50	3.10	2.30	3.20	2.50	2.40	5.37	3.57	5.72	2.91	2.8															
CaO	6.20	6.00	5.60	7.20	5.80	4.9	5.10	7.56	7.19	8.30	5.75	6.59															
Na ₂ O	3.75	4.08	3.55	3.29	3.57	4.14	3.92	2.33	3.38	2.38	3.34	3.22															
K ₂ O	1.53	1.49	2.46	2.47	2.26	2.31	2.73	3.72	3.40	3.83	4.70	4.32															
P ₂ O ₅	1.50	1.33	1.47	1.50	1.37	0.97	1.27	1.02	0.93	1.04	0.99	0.98															
LOI	2.38	2.18	2.70	2.50	1.90	3.07	1.70	2.81	2.55	2.95	1.90	2.23															
Total	99.80	99.85	99.37	99.62	99.29	99.75	99.65	99.33	99.44	99.25	99.29	99.35															
Sc	15	12	15	16	14	12	14	18	14	18	15	15															
V	147	111	152	155	155	112	119	181	147	187	160	163															
Cr	57	46	48	84	54	32	40	148	122	156	126	127															
Co	164	31	64	27	35	22	35	73	25	31	22	24															
Ni	30	21	24	24	29	18	19	73	64	67	56	63															
Ba	1290	1136	1236	1054	1431	1381	1331	3849	2660	4743	3618	3149															
Rb	60.0	38.1	67.0	71.6	99.7	123.9	57.8	49.2	46.1	47.0	63.6	64.2															
Sr	916	749	800	771	938	848	842	1152	1293	1194	1415	1512															
Th	4.81	4.94	6.09	6.25	5.17	4.46	4.12	3.12	2.91	2.91	3.14	3.17															
U	1.04	1.08	1.25	1.34	1.16	0.91	0.91	0.80	0.70	0.76	0.70	0.70															

Zr	431	396	418	434	466	437	394	245	251	254	271	268	139 ± 5	176 ± 6
Hf	9.01	8.29	9.19	9.44	10.01	9.82	8.96	6.13	6.30	6.56	6.80	6.74	3.8 ± 0.1	4.6 ± 0.2
Nb	26.9	21.3	28.8	28.8	31.5	31.7	35.0	29.1	23.4	30.6	25.1	25.1	8.4 ± 0.2	19.2 ± 0.2
Ta	1.50	1.29	1.44	1.50	1.63	1.62	1.86	1.39	1.05	1.51	1.15	1.15	0.60 ± 0.1	1.18 ± 0.02
Y	29.1	22.9	26.4	24.8	30.1	32.7	32.8	21.1	17.7	20.6	18.8	19.0	15.2 ± 0.2	28.0 ± 0.2
La	75.33	67.07	78.19	79.19	86.29	66.98	66.41	69.98	75.08	72.97	81.24	81.46	16.22 ± 0.15	15.16 ± 0.38
Ce	160.5	141.7	162.1	166.6	179.7	141.8	142.6	150.7	159.0	158.7	172.1	171.9	34.5 ± 0.3	37.13 ± 0.84
Pr	18.93	15.84	18.87	18.70	20.73	16.03	16.53	17.35	18.75	18.95	20.08	19.93	4.2 ± 0.2	5.6 ± 0.2
Nd	76.74	62.21	72.77	76.06	83.27	62.65	65.80	70.89	72.62	72.72	77.39	77.62	17.9 ± 0.2	25.9 ± 0.8
Sm	14.90	11.54	13.21	13.61	15.67	12.00	12.07	11.00	10.87	11.80	11.60	11.47	3.8 ± 0.1	6.3 ± 0.2
Eu	3.14	2.30	2.98	2.94	3.36	2.72	2.81	2.63	2.59	2.83	2.82	2.64	1.08 ± 0.05	2.04 ± 0.05
Gd	9.76	7.64	9.23	9.13	10.38	9.00	9.71	7.54	7.11	7.79	7.53	7.66	3.48 ± 0.06	6.35 ± 0.30
Tb	1.27	1.00	1.16	1.02	1.30	1.23	1.29	0.95	0.82	0.93	0.87	0.84	0.52 ± 0.01	0.99 ± 0.04
Dy	6.58	5.25	6.03	5.77	6.83	6.85	7.34	4.36	3.65	4.47	4.03	4.08	3.01 ± 0.03	5.20 ± 0.11
Ho	1.10	0.84	1.01	0.97	1.18	1.25	1.31	0.75	0.59	0.74	0.66	0.67	0.58 ± 0.10	0.96 ± 0.02
Er	2.77	2.26	2.57	2.50	3.22	3.47	3.46	1.86	1.59	1.90	1.74	1.65	1.54 ± 0.03	2.37 ± 0.02
Tm	0.35	0.28	0.29	0.30	0.39	0.45	0.45	0.23	0.21	0.24	0.24	0.22	0.22 ± 0.02	0.34 ± 0.01
Yb	2.19	1.87	2.00	1.87	2.37	3.06	3.13	1.60	1.35	1.50	1.31	1.52	1.35 ± 0.05	2.00 ± 0.02
Lu	0.32	0.27	0.28	0.29	0.33	0.41	0.41	0.20	0.15	0.19	0.18	0.18	0.22 ± 0.01	0.30 ± 0.02

Huajiyang Fm.; D, Donglanggou Fm.; other abbreviations are the same as in Tables 1 and 2.

Jurassic, late Jurassic and early Cretaceous basalts were calculated using ages of 180 Ma, 150 Ma and 120 Ma. Major oxide and trace element compositions and Sr–Nd isotopic data for the samples are listed in Tables 2–4.

Results

Major and trace elements

On a loss on ignition (LOI)-free basis, the studied mafic rocks have 49.9–59.5% SiO₂, 2.4–6.7% MgO, and a Mg-number (Mg-number = $100 \times \text{Mg}/(\text{Mg} + \text{Fe}_T)$ in atomic ratio) range of 34–57. They have medium-K calc-alkaline to high-K calc-alkaline, or even shoshonitic, affinities (Fig. 3). In essence, the Mesozoic Yanshan belt mafic rocks generally have low MgO (or Mg-number), and high Al₂O₃, TiO₂, P₂O₅, Sr, LREE and HFSE relative to the late Mesozoic mafic rocks from the NCB interior (Guo *et al.* 2001, 2003; Fig. 4); these are features of differentiated melts. The main elemental variations of the three basaltic suites are summarized below.

Group 1. The Group 1 rocks have a wide variation in SiO₂ and K₂O (Fig. 3), showing medium-K to high-K calc-alkaline affinities. They span large variations in TiO₂ and P₂O₅ coupled with change in other major and trace elements. On the basis of the compositional gap in TiO₂ and P₂O₅ (Table 1 and Fig. 4), we divided these rocks into two

series: (1) high-Ti and high-P (termed J₁-HTP) and (2) low-Ti and low-P (termed J₁-LTP). The J₁-HTP series have lower SiO₂ and Al₂O₃ but higher HFSE and REE concentrations than the J₁-LTP series. There are no systematic elemental correlations between the two series, implying that they were not comagmatic (Li *et al.* 2004).

Group 2. Like Group 1, the Group 2 rocks are also composed of a low-Ti–P series in the Tiaojishan Fm. (termed J₃-T) and a high-Ti–P series in the Houcheng Fm. (termed J₃-H). The J₃-T samples have higher Al₂O₃ (17.5–20.0%) and Sr (845–1408 ppm), low Y (13.1–17.9 ppm), high Sr/Y (52–95) and strong LREE/HREE (heavy REE) fractionation (i.e. La/Yb_{CN} = 15.9–23.0), features of adakitic magmas (Fig. 5; e.g. Defant & Drummond, 1990; Martin *et al.* 2005). A slight change in REE, Th and Nb, and a decrease in FeO_T, Al₂O₃, CaO and Sr are coincident with an increase in SiO₂. The J₃-H basalts show shoshonitic affinities and narrow changes in major and trace elements (e.g. SiO₂ 49.4–52.1%, MgO 2.6–4.5%) except for La (54.9–88.4 ppm) and Sr (1317–2033 ppm). They are evolved magmas, according to their low MgO and Cr (12–115 ppm) and Ni (16–24 ppm) concentrations.

Group 3. The Group 3 mafic volcanic rocks span a SiO₂ range of 50.2–56.0% and a MgO range of 2.4–5.9%, showing high-K calc-alkaline to shoshonitic affinities (Fig. 3). They generally have higher LREE and HFSE concentrations than the other two groups (Table 3 and Fig. 4). Samples from the Huajiyang Fm. (termed K₁-H) have the lowest MgO and highest P₂O₅ and Th of the studied rocks (Table 3). Following an increase in SiO₂, they show decrease in FeO_T, CaO, TiO₂, P₂O₅, LREE and Th, an increase in Nb, and weak Sr variation (Fig. 4). The other rocks from the Donglingtai Fm. (termed K₁-D) demonstrate a decrease in MgO, FeO_T, TiO₂, Nb and Sr, an increase in LREE, and weak variation in Al₂O₃, P₂O₅ and Th following magma evolution.

All the Mesozoic Yanshan belt mafic volcanic rocks are characterized by significant LILE and LREE enrichment, and depletion in Nb–Ta (e.g. La/Nb = 1.9–4.6 and Ba/Nb = 37–273) and Th–U (e.g. Th/La = 0.039–0.10, with an average of 0.062) in primitive mantle-normalized incompatible element spidergrams (Fig. 6), features very different from those of MORB and OIB (Sun & McDonough 1989).

Sr and Nd isotopes

The analytical and age-corrected Sr and Nd isotopic data for the Mesozoic Yanshan belt mafic lavas are

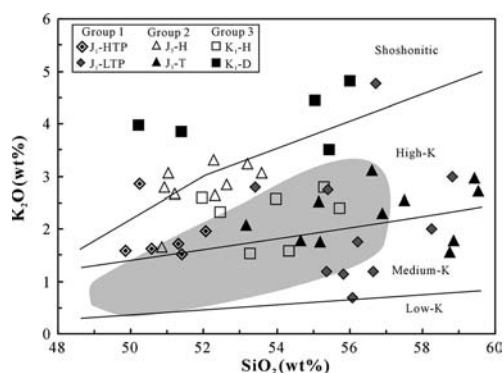


Fig. 3. SiO₂ v. K₂O classification diagram for the Mesozoic Yanshan belt basalts (after Middlemost 1994). The late Mesozoic NCB interior mafic rocks (Guo *et al.* 2001, 2003, and unpublished data) are plotted for comparison (the shaded area). J₁-HTP, high-Ti–P series from the Nandaling Fm.; J₁-LTP, low-Ti–P series from the Nandaling Fm.; J₃-T, samples from the Tiaojishan Fm.; J₃-H, samples from the Houcheng Fm.; K₁-D, samples from the Donglingtai Fm.; K₁-H, samples from the Huajiyang Fm.

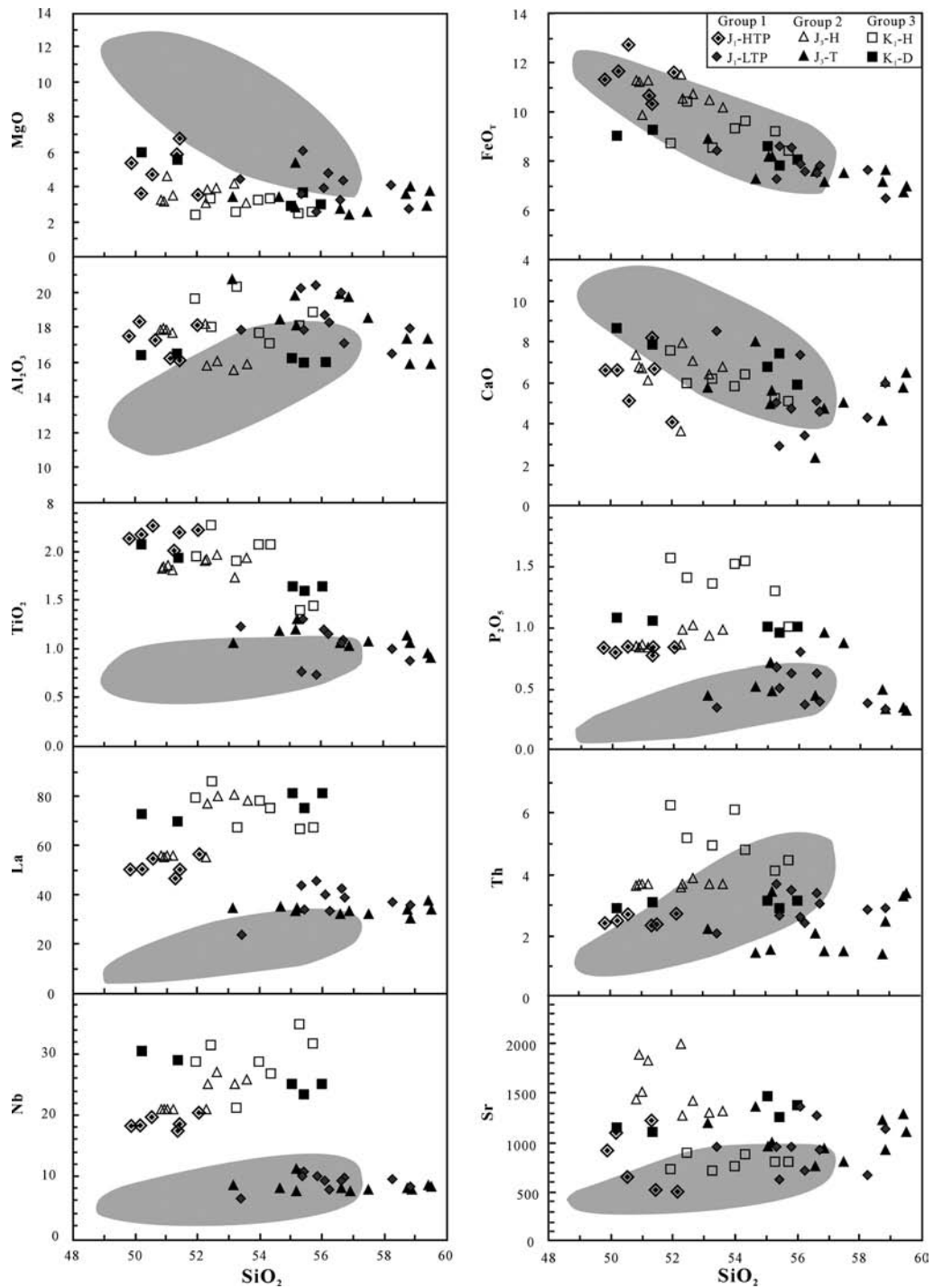


Fig. 4. SiO_2 v. major elements (in wt%) and trace elements (in ppm) for the Mesozoic Yanshan belt mafic rocks. The shaded areas show the variation fields of the late Mesozoic NCB interior mafic rocks. Data sources and symbols are as in Figure 3.

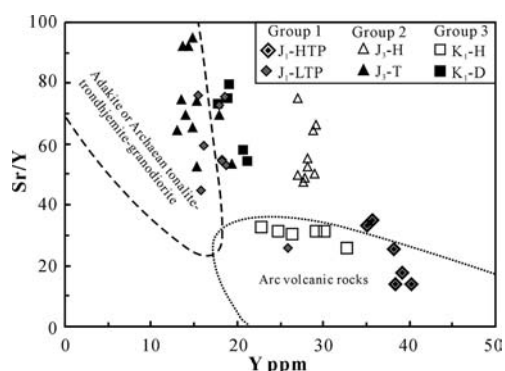


Fig. 5. Sr v. Sr/Y for the Mesozoic Yanshan belt mafic volcanic rocks. It should be noted that some J₃-H and J₁-LTP samples have low Y and high Sr/Y ratios similar to modern adakites or Archean tonalite-trondhjemitic-granodiorites.

listed in Table 4. These rocks generally exhibit fairly large variations in Sr and Nd isotope compositions. In Group 1, two J₁-HTP samples have initial $^{87}\text{Sr}/^{86}\text{Sr}(i)$ of c. 0.7060 and $\varepsilon_{\text{Nd}}(t)$ of c. -7.5 , similar to the high-Mg andesites from the northern NCB (Zhang *et al.* 2003), but different from the J₁-HTP rocks, which have an $^{87}\text{Sr}/^{86}\text{Sr}(i)$ range of 0.7052–0.7061 and $\varepsilon_{\text{Nd}}(t)$ range from -15.1 to -12.1 . In Group 2, the J₃-H samples span an $^{87}\text{Sr}/^{86}\text{Sr}(i)$ range of 0.7053–0.7061 and an $\varepsilon_{\text{Nd}}(t)$ range from -14.9 to -13.5 , overlapping the variation field of the J₁-HTP rocks (Fig. 7); $^{87}\text{Sr}/^{86}\text{Sr}(i)$ ranges from 0.7064 to 0.7066 and $\varepsilon_{\text{Nd}}(t)$ from -14.1 to -11.8 for the J₃-H rocks. In Group 3, the K₁-D rocks have an $^{87}\text{Sr}/^{86}\text{Sr}(i)$ range of 0.7057–0.7059, $\varepsilon_{\text{Nd}}(t)$ from -14.8 to -12.5 , and less radiogenic Sr and Nd isotopic compositions than the K₁-H samples, which span an

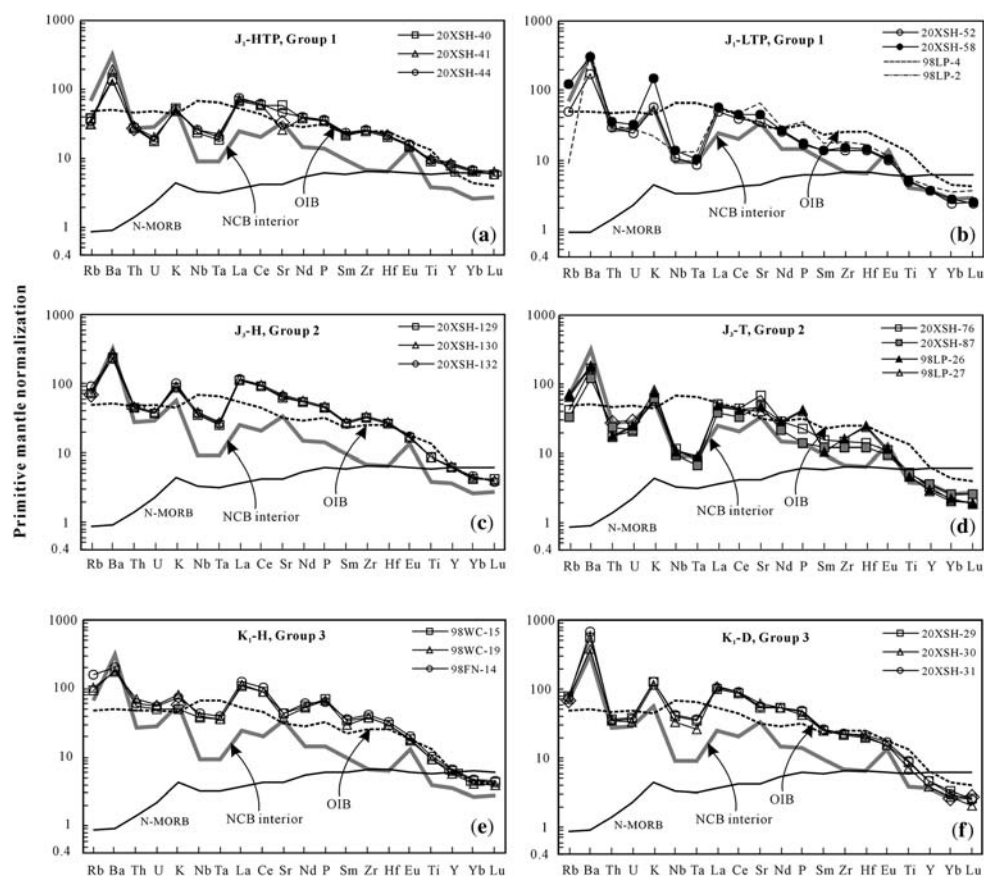


Fig. 6. Primitive mantle-normalized incompatible element spidergrams of Mesozoic Yanshan belt basalts. All the basaltic samples show remarkable Th–U and Nb–Ta negative anomalies relative to Ba and La. Data for the late Mesozoic NCB interior mafic rocks are from Guo *et al.* (2001, 2003); data for PM, OIB and N-MORB are from (Sun & McDonough 1989).

Table 4. *Sr and Nd isotope data of Mesozoic mafic volcanic rocks from the Yanshan belt*

Sample	Rb (ppm)	Sr (ppm)	Sm (ppm)	Nd (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr} \pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}(t)^*$	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd} \pm 2\sigma$	$\epsilon_{\text{Nd}}(t)$
<i>Group 1</i>										
98LP-2	14.9	1313	7.97	43.49	0.0328	0.705308 $\pm$ 14	0.7052	0.1107	0.511873 $\pm$ 10	-12.9
98LP-4	5.76	1400	7.79	39.74	0.0119	0.705443 $\pm$ 16	0.7054	0.1185	0.511632 $\pm$ 6	-15.1
98LP-8	22.9	998	8.08	45.70	0.0664	0.705631 $\pm$ 16	0.7055	0.1069	0.511721 $\pm$ 10	-13.4
20XSH-40	24.1	1243	9.40	51.81	0.0562	0.706091 $\pm$ 14	0.7059	0.1097	0.512020 $\pm$ 11	-7.5
20XSH-41	19.9	541	9.84	52.16	0.1067	0.706346 $\pm$ 16	0.7061	0.1141	0.512018 $\pm$ 13	-7.6
20XSH-57	28.5	708	6.02	34.81	0.1163	0.706383 $\pm$ 13	0.7061	0.1045	0.511773 $\pm$ 13	-12.4
20XSH-58	77.9	958	6.19	35.97	0.2354	0.706629 $\pm$ 17	0.7060	0.1040	0.511784 $\pm$ 12	-12.1
20XSH-59	49.7	668	8.08	42.99	0.2154	0.706404 $\pm$ 17	0.7059	0.1137	0.511711 $\pm$ 11	-13.6
<i>Group 2</i>										
98LP-24	42.7	1012	7.72	39.0	0.1220	0.705547 $\pm$ 17	0.7053	0.1196	0.511819 $\pm$ 9	-14.6
98LP-26	40.4	972	7.64	39.8	0.1204	0.705672 $\pm$ 17	0.7054	0.1162	0.511832 $\pm$ 8	-14.4
98LP-27	44.6	845	7.18	37.8	0.1528	0.705651 $\pm$ 18	0.7054	0.1149	0.511797 $\pm$ 12	-14.9
20XSH-77	28.8	1263	6.59	37.22	0.0661	0.706133 $\pm$ 16	0.7061	0.1070	0.511806 $\pm$ 11	-14.5
20XSH-85	67.0	1138	5.54	31.18	0.1756	0.706183 $\pm$ 11	0.7058	0.1074	0.511830 $\pm$ 11	-14.1
20XSH-88	28.5	970	5.49	31.17	0.0852	0.705937 $\pm$ 10	0.7058	0.1065	0.511856 $\pm$ 12	-13.5
20XSH-122	43.2	1929	9.76	57.11	0.0649	0.706766 $\pm$ 10	0.7066	0.1033	0.511856 $\pm$ 11	-11.8
20XSH-123	53.3	1557	10.06	57.47	0.0991	0.706818 $\pm$ 10	0.7066	0.1058	0.511853 $\pm$ 10	-11.8
20XSH-125	48.1	1862	10.12	56.56	0.0748	0.706931 $\pm$ 20	0.7066	0.0976	0.511817 $\pm$ 9	-12.5
20XSH-132	58.0	1361	11.83	72.31	0.1223	0.706679 $\pm$ 18	0.7064	0.0989	0.511733 $\pm$ 10	-14.1
<i>Group 3</i>										
98WC-15	60.0	916	14.90	76.74	0.1894	0.706861 $\pm$ 14	0.7065	0.1174	0.512114 $\pm$ 9	-7.2
98WC-19	67.0	800	13.21	72.77	0.1471	0.707067 $\pm$ 16	0.7068	0.1097	0.512036 $\pm$ 8	-8.7
98WC-20	71.6	771	13.61	76.06	0.2684	0.707002 $\pm$ 18	0.7065	0.1081	0.512046 $\pm$ 8	-8.5
98FN-14	99.7	938	15.67	83.27	0.3077	0.707216 $\pm$ 13	0.7067	0.1138	0.511997 $\pm$ 8	-9.5
98FN-20	57.8	842	12.07	65.80	0.1986	0.706623 $\pm$ 17	0.7063	0.1109	0.512007 $\pm$ 10	-9.3
20XSH-29	49.2	1152	11.00	70.89	0.1237	0.705984 $\pm$ 16	0.7058	0.0938	0.511855 $\pm$ 8	-12.5
20XSH-30	46.1	1293	10.87	72.62	0.1031	0.705939 $\pm$ 14	0.7058	0.0905	0.511735 $\pm$ 8	-14.8
20XSH-31	47.0	1194	11.80	72.72	0.1138	0.705901 $\pm$ 16	0.7057	0.0981	0.511847 $\pm$ 8	-12.7
20XSH-32	63.6	1415	11.60	77.39	0.1300	0.706087 $\pm$ 18	0.7059	0.0906	0.511805 $\pm$ 11	-13.5

*The initial Sr and Nd isotope data Group 1, 2 and 3 basalts are recalculated using a mean age of 180 Ma, 150 Ma and 120 Ma, respectively.

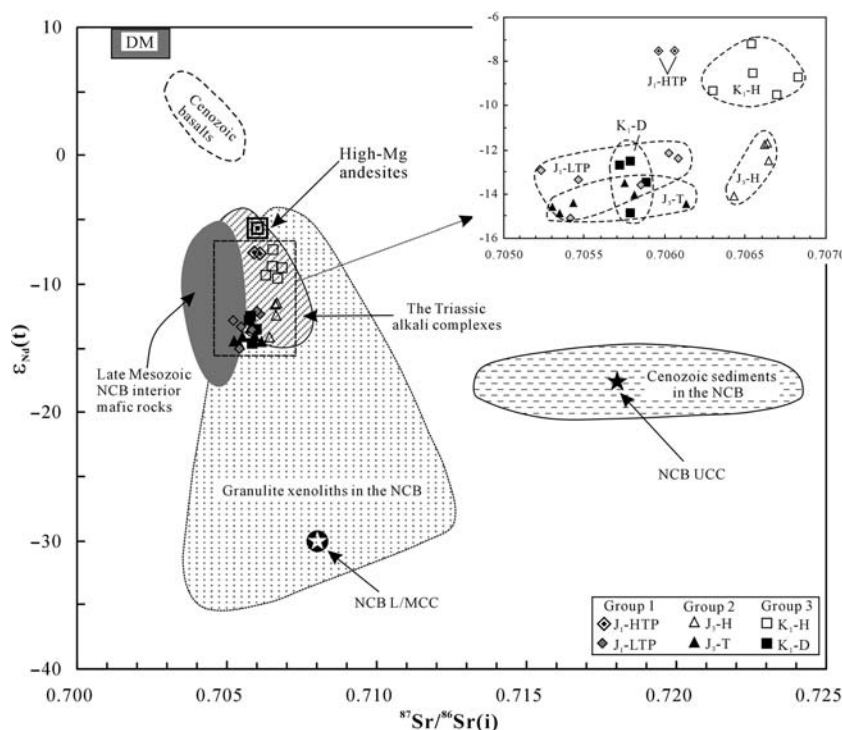


Fig. 7. $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ v. $\epsilon_{\text{Nd}}(t)$ for the Mesozoic Yanshan belt basalts. Data for the high-Mg andesites are from Zhang *et al.* (2003); for the Triassic alkaline intrusive complexes from Yan *et al.* (2000); for the NCB upper crust from our unpublished data for Cenozoic NCB sediments); for granulite-facies xenoliths from Zhang *et al.* (1998); Zhou *et al.* (2002); Huang *et al.* (2004) and Li Huang *et al.* (2004); for the late Mesozoic NCB interior mafic rocks from Guo *et al.* (2001, 2003, and unpublished data).

$^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ range of 0.7063–0.7068 and $\epsilon_{\text{Nd}}(t)$ range of –9.5 to –7.2.

In essence, the Yanshan belt mafic rocks generally have higher $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ ratios (0.7052–0.7068) than those of late Mesozoic counterparts from the NCB interior (Fig. 7), which span an $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ range of 0.7040–0.7057 (Guo *et al.* 2001, 2003).

Petrogenesis of the Mesozoic Yanshan belt mafic lavas

The Mesozoic Yanshan belt mafic lavas have MgO, Cr and Ni values too low to represent primary mantle-derived magmas (e.g. Hart & Davis 1978). To account for their enriched character (e.g. LREE and LILE and Sr–Nd isotopes), the petrogenesis of the three groups necessitates the involvement of: (1) an enriched component, either asthenospheric (e.g. a deep mantle plume) or lithospheric in origin, or (2) enrichment processes, such as high degrees of fractional crystallization, crustal contamination or assimilation–fractional

crystallisation (AFC). Below, we will evaluate the effect of both magmatic processes and source characteristics on magma evolution. In addition, a geochemical comparison with the late Mesozoic NCB interior mafic rocks is also presented, to show the possible difference of SCLM between cratonic and circumcratonic regions.

Crustal contamination

Basalts erupted in continental settings are often enriched in incompatible trace elements and isotopic features relative to their oceanic counterparts. The debate continues as to the importance of processes operating at crustal levels, which makes it necessary to evaluate the possible effects of crustal contamination or AFC. All the Mesozoic Yanshan belt mafic rocks show significant Nb–Ta depletion relative to LILE and LREE, radiogenic Sr and unradiogenic Nd isotopic compositions. Mass balance consideration suggests that such geochemical features in the Yanshan belt mafic rocks cannot be realistically attributed to crustal contamination of asthenosphere-derived melts

such as normal MORB (N-MORB) and OIB (e.g. Hawkesworth *et al.* 1995; Jahn *et al.* 1999; Fan *et al.* 2003).

However, if the primary magmas were derived from enriched mantle sources, the variable Sr–Nd isotope data for the three groups might have been a result of crustal contamination or AFC. To discuss the role of crustal contamination and/or AFC during magmatic evolution, we selected the possible endmember components to model these possibilities. Sample 98LP-2 has the lowest $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$, and thus it is assumed to represent the least contaminated primary melt for Sr isotopic modelling. Because we have only two HTP samples from Group 1, it is difficult to evaluate the role of crustal contamination in their petrogenesis, but the fact that they have the highest MgO and almost the highest $\epsilon_{\text{Nd}}(t)$ of all studied rocks indicates that they represent the least contaminated melts. Here we select sample 20XSH-41, which has the highest MgO (6.44%) and higher $\epsilon_{\text{Nd}}(t)$ value (–7.6), to represent the least contaminated magma for Nd isotopic calculation. The modelling results for both crustal contamination and AFC processes are illustrated in Figure 8.

The K₁-H samples, which have the lowest MgO and the highest $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ of all the studied rocks, are the most likely candidates for contaminated melts. Sr isotopic modelling results require addition of 40–50% NCB upper continental crust (UCC) to magma like 98LP-2 to produce the higher $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ in these rocks (Fig. 8a). However, addition of such a large volume of cold NCB UCC could not be re-equilibrated for heat budget. AFC processes could be another possibility to generate their higher $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$. The AFC modelling result shows that with a K_{D}^{Sr} range of 0.8–1.2 and remaining magma fraction (F) < 0.3 (Fig. 8b), these rocks could be produced by assimilation of the NCB UCC. However, such a low F would lead to a high extent of ferromagnesian fractionation during magma evolution, which should have created an evolved magma of felsic rather than mafic composition as observed at present. Accordingly, neither crustal contamination nor AFC was predominant in the magma evolution of the K₁-H rocks.

The J₁-LTP and J₃-T samples, which have $\epsilon_{\text{Nd}}(t)$ 4–8 units lower than the J₁-HTP and K₁-H rocks, may have resulted from crustal contamination and/or AFC. As illustrated in Figure 8c, both the J₁-LTP and J₃-T samples could be formed by addition of 50–80% NCB UCC or 40–60% NCB lower or middle continental crust (LCC or MCC) to magma like 20XSH-41. For heat budget reasons, such a high volume of contamination is unlikely to happen. AFC could be another process to produce their lower $\epsilon_{\text{Nd}}(t)$. The AFC modelling

result indicates that with a K_{D}^{Nd} range of 0.8–1.2 and remaining magma fraction F < 0.2, assimilation of either the NCB UCC or LCC–MCC to melt like 20XSH-41 would produce the Nd isotopic compositions in these two groups of rocks (Fig. 8d). Similarly, the magma produced should have been felsic rather than mafic composition. Therefore crustal contamination or AFC should be subordinate even if it did occur.

The remaining J₃-H and K₁-D rocks, which plot away from the crustal contamination trend and have less varied Sr and Nd isotope data compared with the other groups from the Yanshan belt, escaped significant crustal contamination. For instance, Sr isotopic modelling results show that with F < 0.4, assimilation of either NCB UCC or NCB LCC–MCC would create the observed Sr isotopic compositions in these samples (Fig. 8b); whereas with F < 0.2, assimilation of either NCB UCC or NCB LCC–MCC would generate the observed Nd isotopic compositions (Fig. 8d).

In summary, crustal contamination or AFC had an insignificant effect on the magma evolution of the studied Mesozoic Yanshan belt mafic rocks. The Sr–Nd isotopic variations in these rocks were mainly inherited from a heterogeneous source.

Fractional crystallization

As mentioned above, all the studied mafic lavas from the Yanshan belt show an evolved affinity, with low MgO and compatible trace element contents, which would require a significant role of fractional crystallization during magma evolution. In Group 1, the compositional gaps in TiO₂, P₂O₅ and other incompatible elements (e.g. REE and HFSE) between the J₁-HTP and J₁-LTP series cannot be produced through fractional crystallization of a common primary magma (Li *et al.* 2004), so the two series had distinct fractional phases during their passage through the lithosphere. The J₁-HTP samples show weak variations in major and trace elements and have the highest MgO, indicating an insignificant role of fractional crystallization *en route* to the surface. In contrast, fractionation of a few percent of ferromagnesian phases and plagioclase and minor Ti-rich phases (e.g. rutile, ilmenite and Ti-magnetite) is necessary to account for the broad decrease in MgO, FeO_T, CaO, Al₂O₃, TiO₂ and HFSE in the J₁-LTP series.

Similarly, the compositional gaps in Al₂O₃, TiO₂, P₂O₅, LREE and HFSE between the J₃-T and J₃-H samples in Group 2 suggest that the two subgroups were not comagmatic in origin. Intensive ferromagnesian fractionation (e.g. olivine and clinopyroxene) is essential to explain their low MgO, FeO_T, CaO and other compatible elements

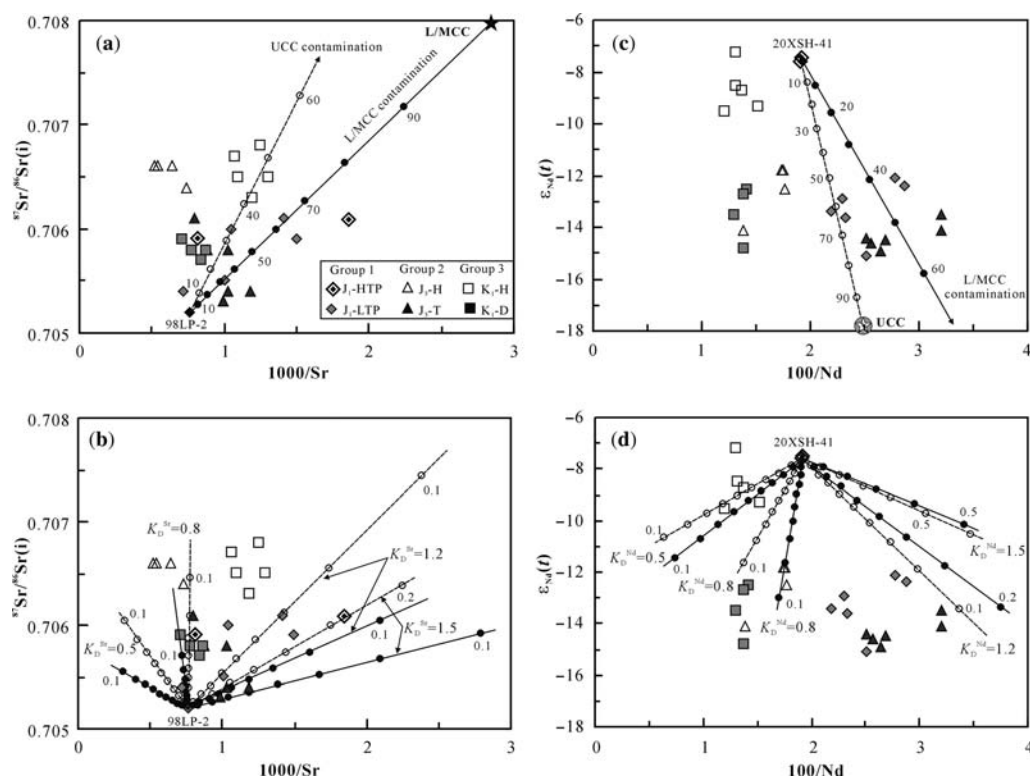


Fig. 8. $1000/\text{Sr}$ v. $^{87}\text{Sr}/^{86}\text{Sr}(i)$ (a, b) and $100/\text{Nd}$ v. $\epsilon_{\text{Nd}}(t)$ (c, d) for the Mesozoic Yanshan belt mafic rocks, showing the possible effect of crustal contamination and AFC during magma evolution. (a) and (c) show bulk contamination of possible crustal components; (b) and (d) show AFC trends. The calculation endmembers are: the NCB UCC: Sr 210 ppm, Nd 40 ppm, $^{87}\text{Sr}/^{86}\text{Sr}(i) = 0.716$; $\epsilon_{\text{Nd}}(t) = -18$ (our unpublished data from Cenozoic sedimentary rocks in the NCB); the supposed NCB LCC–MCC: Sr 350 ppm, Nd 20 ppm, $^{87}\text{Sr}/^{86}\text{Sr}(i) = 0.708$; $\epsilon_{\text{Nd}}(t) = -30$ (Jahn & Zhang 1984; Zhou *et al.* 2002; Liu *et al.* 2004); 98LP-2: Sr 1323 ppm, $^{87}\text{Sr}/^{86}\text{Sr}(i) = 0.7052$; 20XSH-41: Nd 52 ppm, $\epsilon_{\text{Nd}}(t) = -7.6$. In the AFC modelling, the assimilation rate (r) is assumed to be 0.25. (See details in the text.) Tick marks on the AFC curves represent increments of 0.1 remaining magma fraction (F).

(e.g. Cr and Ni). Plagioclase fractionation is insignificant, as both subgroups have fairly high Sr contents.

For the K₁-D samples in Group 3, a fractional assemblage of olivine + clinopyroxene ± ilmenite ± apatite is required to account for the rapid decrease in MgO, FeO_T, CaO, TiO₂ and P₂O₅ following magma evolution. Plagioclase fractionation is subordinate, as both Al₂O₃ and Sr show little variation over the wide range of SiO₂. The K₁-H rocks, which have the lowest MgO, and highest P₂O₅ and Th, require intensive ferromagnesian and plagioclase fractionation and subordinate apatite fractionation before extrusion to surface.

Source characteristics

In recent years, geochemical investigations of the Mesozoic mafic rocks, and of Cenozoic

basalt-hosting granulite and pyroxenite xenoliths, have revealed the existence of highly enriched but heterogeneous mantle sources beneath the northern NCB (e.g. Zhang *et al.* 1998; Yan *et al.* 2000; Shao *et al.* 2001; Zhou *et al.* 2001, 2002; Xu 2002; Zhang *et al.* 2003; Li *et al.* 2004; Liu *et al.* 2004). Debate still continues about the timing and mechanism of the enrichment event(s). Possible models are: Mesozoic lithospheric delamination to account for lithospheric thinning and incompatible element enrichment in the NCB (e.g. Gao *et al.* 1998, 2004; Liu *et al.* 2004); slab-modified lithospheric mantle to explain the petrogenesis of high-Mg andesites (Zhang *et al.* 2003); multiple-stage enrichment processes related to recycling of NCB crust to form the pyroxenite xenoliths (Xu 2002); and lower crust–lithospheric mantle interaction to explain the radiogenic Sr and unradiogenic Nd and Pb isotopic compositions in the granulite xenoliths of

Mesozoic ages (Zhang *et al.* 1998; Zhou *et al.* 2002; Wilde *et al.* 2003). However, available Sr–Nd–Pb isotope data for mafic rocks with ages from 245 to 110 Ma, including basalts, high-Mg andesites, mafic cumulates and granulite xenoliths hosted in Cenozoic basalts, indicate radiogenic Sr and unradiogenic Nd and Pb isotopic compositions (Zhang *et al.* 1998, 2003; Li *et al.* 2001, 2004; Shao *et al.* 2001; Zhou *et al.* 2001, 2002; Gao *et al.* 2004). These data at least indicate that before the early Mesozoic an enrichment event occurred during the evolution of lithospheric mantle beneath the Yanshan belt.

Because of the insignificant role of crustal contamination or AFC during magma evolution, the strong depletion in Nb–Ta and Th–U, and moderately radiogenic Sr and unradiogenic Nd isotopic compositions in the Yanshan belt, the mafic rocks require their derivation from a LILE- and LREE-enriched lithospheric mantle. The adakitic trace element features in the J₃-T basaltic andesites suggest a significant contribution of slab melts in the melting mantle source (Rogers *et al.* 1985; Saunders *et al.* 1987; Calmus *et al.* 2003; Martin *et al.* 2005), rather than interaction between melts derived from delaminated eclogitic crust and upper mantle as suggested by Gao *et al.* (2004). We thus relate the enrichment process to the subduction of the palaeo-Asian Ocean during late Palaeozoic–early Mesozoic time (e.g. Sengör & Natal'in 1996; Robinson *et al.* 1999; Shi *et al.* 2003; Miao *et al.* 2004).

It is noteworthy that the considerable U–Th troughs in the spidergrams and relatively higher TiO₂ contents in the least evolved samples (e.g.

20XSH-41, TiO₂ 2.11%) from the Yanshan belt are distinguishable from the results for most arc basalts (e.g. Arculus 1994; Hunter & Blake 1995; Macdonald *et al.* 2000; Jolly *et al.* 2001; Plank 2005). Based on Th/La values of global arc basalts and the subducting sediments, Plank (2005) attributed the Th/La ratios in arc basalts to mixing between the underlying mantle wedge and the subducting sediments. He further pointed that where the subducting sediment has Th/La > 0.2, the arc basalts generally have Th/La > 0.15, and where the sediment has a value < 0.2, the arc basalts commonly have a value < 0.15 (Plank 2005). The Mesozoic Yanshan belt mafic volcanic rocks have low Th/La (0.039–0.10), with some samples from the J₃-T and K₁-D having even lower Th/La than N-MORB (Th/La = 0.048, Sun & McDonough, 1989), calling for involvement of extremely low-Th/La crustal materials in their melting source, such as lower crustal granulite xenoliths or CaO- and P₂O₅-rich marine sediments (Plank 2005, and references therein; see also Huang & Frey 2005). The other samples, which have higher Th/La ratios than N-MORB, require the addition of relatively high-Th/La crustal rocks (Fig. 9), such as terrigenous sediments and/or continental upper crust. However, the generally low Th/La ratios in the Mesozoic Yanshan belt mafic rocks suggest that the involved crustal components also have a bulk low Th/La (e.g. < 0.2) according to the Th/La estimation from modern arcs (Plank 2005). The most likely candidates are the Archaean high-grade metamorphic terranes or lower/middle crust of the NCB, which have low Th/La and radiogenic Sr and unradiogenic Nd isotopic

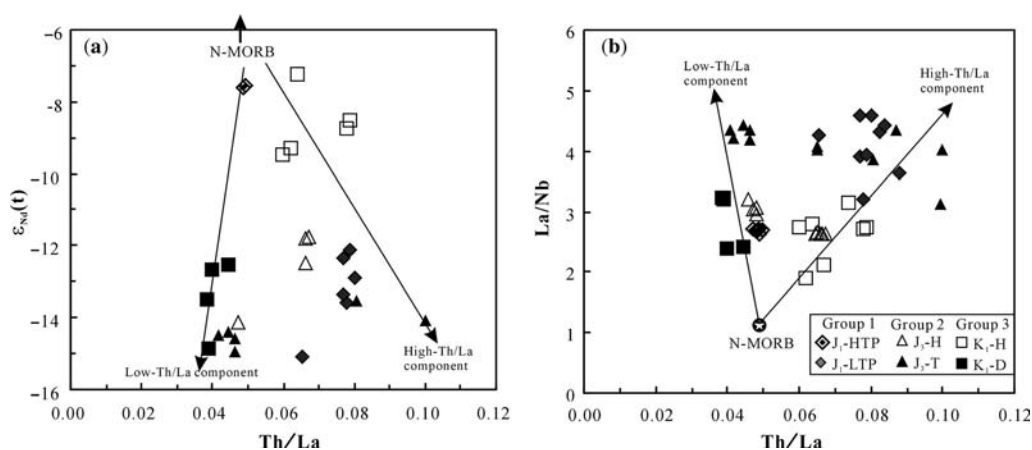


Fig. 9. Th/La v. $\epsilon_{\text{Nd}}(t)$ (a) and La/Nb (b) for the Mesozoic Yanshan belt mafic rocks. The extremely low Th/La (< 0.048, N-MORB) in some samples suggests the contribution of a low-Th/La, low $\epsilon_{\text{Nd}}(t)$ and high La/Nb component (Sun & McDonough 1989), whereas the other samples require a high-Th/La and La/Nb, and low- $\epsilon_{\text{Nd}}(t)$ endmember in the melting source. (See discussion in the text).

compositions (Jahn & Zhang 1984; Huang *et al.* 2004; Liu *et al.* 2004; Zhou *et al.* 2002).

One possibility to introduce the low-Th/La crustal materials into the melting mantle source is that they were eroded and deposited as terrigenous sediments and were dragged down into the mantle wedge together with the subducting palaeo-Asian slab during the late Palaeozoic to early Mesozoic (e.g. Sengör & Natal'in 1996; Robinson *et al.* 1999; Shi *et al.* 2003; Miao *et al.* 2004). Another possibility is that the palaeo-Asian Ocean was an intracontinental oceanic basin, in which the NCB lower continental crust remained. For instance, there exist inherited Archaean zircons in the mafic components of the Hegenshan ophiolite (e.g. Miao *et al.* 2006). During the slab subduction, both the oceanic crust and the NCB lower crustal materials or recycled Archaean high-grade metamorphic terranes were dragged down into the mantle. Interaction of these ancient crustal materials with the mantle beneath the northern NCB would form a mantle reservoir enriched in LREE and LILE but of low Th and U, radiogenic Sr, and unradiogenic Nd and Pb isotopic compositions.

Comparison with the NCB lithospheric mantle

The geochemical differences between the late Mesozoic NCB interior and the Yanshan belt mafic lavas (Figs 4, 6 and 7) also indicate mantle heterogeneity between cratonic and circumcratonic regions. Geochemistry of the late Mesozoic NCB interior mafic rocks reveals the existence of a chemically refractory and long-term LILE- and LREE-enriched mantle reservoir, which is a feature of subcratonic lithospheric mantle (Guo *et al.* 2001, 2003; Zhang *et al.* 2004). In the following discussion, we compile available data to show the differences between the SCLM beneath the two regions for major element considerations.

An approach commonly used for comparison of basalt data to distinguish mantle domains is to extrapolate the less evolved rocks to 8% MgO, beyond which fractionation is believed to be largely dominated by olivine (Klein & Langmuir 1987). As the Mesozoic Yanshan belt mafic rocks are fairly well evolved in terms of major element compositions (e.g. Mg-number <60, and mainly 45–57 for samples with MgO > 4.5%), the assumption that the fractionating assemblage remains constant when extrapolated back to 8% MgO is difficult to verify (e.g. Garland *et al.* 1996). Where obvious inflections in the trends occur as a result of changes in the fractionating assemblage a line is fitted to the most primitive portion of the trend, and obvious outliers are

eliminated. Extrapolation of the Mesozoic Yanshan belt basalts and the late Mesozoic NCB interior mafic rocks to 8% MgO has been carried out by fitting a simple correlation line; only samples with a MgO range of 4.5–10% are regressed, following the method and rationale of Turner & Hawkesworth (1995). The calculation results are listed in Table 5.

The Yanshan belt basalts and mafic dykes (Shao *et al.* 2001) span a Si₈ range of 43.9–51.3%, Fe₈ range of 9.3–13.8% and Ti₈ range of 1.8–3.3%. Compared with the late Mesozoic NCB interior counterparts (Guo *et al.* 2001, 2003, and unpublished data), they have higher Fe₈, Ti₈ and lower Si₈ (Fig. 10a and b). In contrast to the late Mesozoic NCB mafic rocks, which have moderately varied Na₈ (2.2–3.3%), the Yanshan belt rocks have a relatively larger Na₈ range from 1.6 to 4.0% (Fig. 10c), a result of either surface alteration or the incorporation of residual Na in the jadeite component of clinopyroxene during melting (e.g. Klein & Langmuir 1987; Turner & Hawkesworth 1995; Garland *et al.* 1996). As shown in Figure 10b and d, there are no coherent variations between the Mesozoic mafic rocks from the two areas; in particular, there is a Ti₈ gap from 0.9 to 1.8%.

Experimental results from peridotite melting reveal that the Fe content of a melt is positively correlated with pressure and source composition; thus a melt either at high pressures or derived from a fertile source will have high Fe (e.g. Hirose & Kushiro 1993; Baker & Stolper 1994). In contrast, the Si content is negatively correlated with melting pressure and increases in the presence of fluid. The Ti content is a gauge of source fertility and is sensitive to melt removal. Na mainly reflects the degree of melting, as it acts as an incompatible element under mantle conditions. At high pressures, Na is less incompatible, as it is retained in the residue incorporated in the jadeite component of clinopyroxene. Compared with experimental results (e.g. Kushiro 1990; Hirose & Kushiro 1993; Baker & Stolper 1994), the higher Si₈, Fe₈ and Ti₈ in the Yanshan belt basalts than those of the late Mesozoic NCB interior mafic rocks can be attributed to either variation in melting conditions (e.g. pressure and melting degree) or source heterogeneity, or both (Fig. 10).

Because Th and U are highly incompatible elements during melting, Th and U contents in basalts are sensitive to the extent of melting. As can be seen in the Th v. U diagram (Fig. 11), both the Yanshan belt and the NCB interior mafic rocks with a MgO range of 4.5–10% have comparable Th and U contents, suggesting that melting degree was not a major factor to account for the Ti₈ gap between the mafic rocks from the two

Table 5. Averages at wt% MgO for selected major elements of the late Mesozoic mafic rocks from the NCB interior and the Yanshan belt

Locality	Number of samples	Si ₈ average ± 1σ	R ²	Fe ₈ average ± 1σ	R ²	Ti ₈ average ± 1σ	R ²	Na ₈ average ± 1σ	R ²
The NCB interior	19	52.38 ± 0.85	0.51	8.17 ± 0.70	0.03	0.81 ± 0.01	0.45	2.56 ± 0.10	0.77
The Yanshan belt	15	47.50 ± 5.24	0.04	10.64 ± 0.41	0.11	2.51 ± 0.16	0.22	3.24 ± 0.97	0.05

Correction of the data was carried out using the equation $X_8 = (\text{slope} \times 8 + X_{\text{sample}}) - (\text{slope} \times \text{MgO}_{\text{sample}})$.

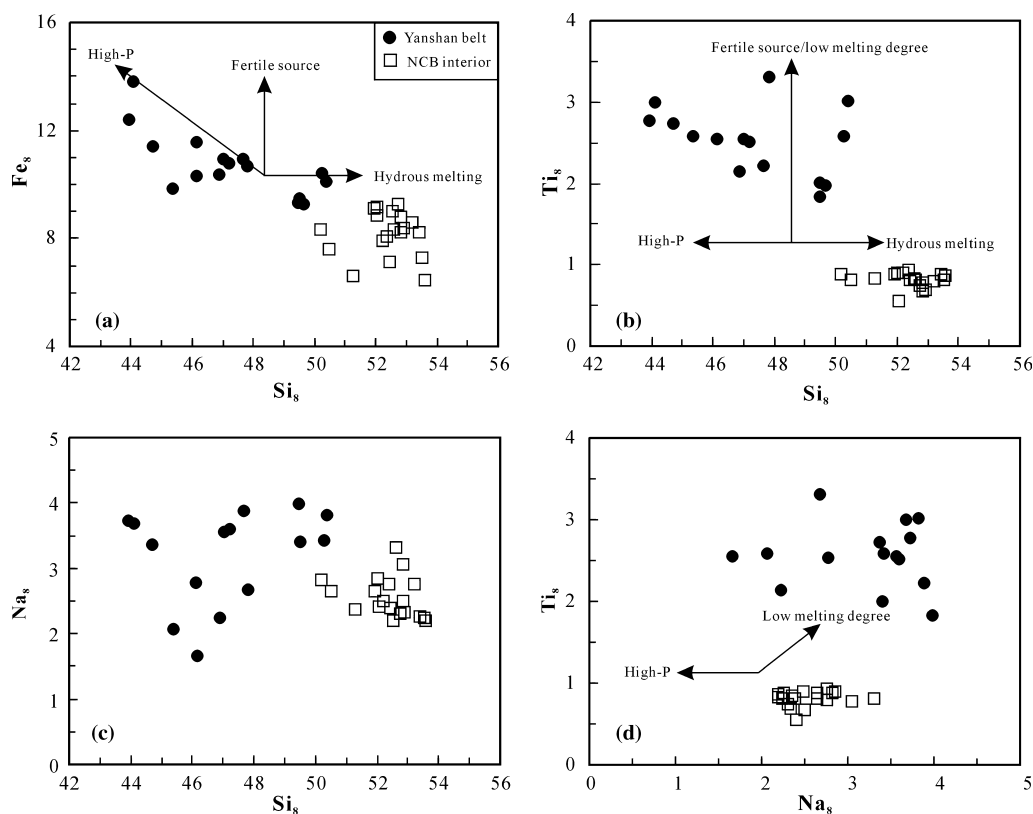


Fig. 10. Si_8 v. Fe_8 , Ti_8 and Na_8 and Na_8 v. Ti_8 for the Mesozoic Yanshan belt basalts and late Mesozoic NCB mafic rocks, showing the possible effect of melting conditions and source composition. The higher Fe_8 and Ti_8 but lower Si_8 contents in the Mesozoic Yanshan belt basalts reflect a relatively fertile source in the origin. Samples with a MgO range of 4.5–10% are selected for 8% MgO extrapolation. Data sources are as in Figure 3.

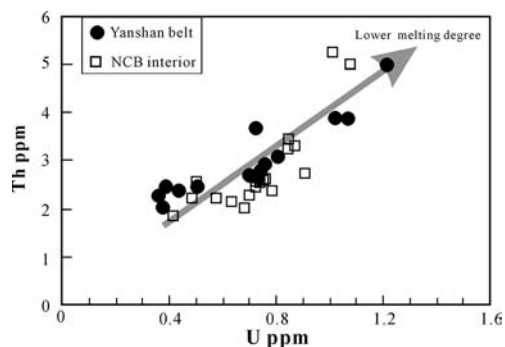


Fig. 11. Th v. U for Mesozoic Yanshan belt basalts, showing possible effect of magmatic processes on magma evolution. Samples with a MgO range of 4.5–10% are selected for comparison. Data source are as in Figure 3.

regions, even if these melts had been derived from a common source. We thus consider the Ti_8 gap as a result of source difference; that is, there was a more fertile mantle source beneath the Yanshan belt than beneath the NCB interior. Irrespective of the effect caused by melting pressure on melt composition, the relatively fertile mantle source would also explain the lower Si_8 and higher Fe_8 in the Yanshan belt basalts.

In summary, the lower Si_8 but higher Fe_8 and Ti_8 in the mafic rocks from the Yanshan belt compared with those in the NCB interior indicate that they were probably derived from a chemically fertile mantle reservoir, different from the Mesozoic chemically refractory mantle reservoir beneath the NCB interior (Guo *et al.* 2001, 2003). Such a difference is also reflected by the generally higher Sr isotope ratios in the Yanshan belt mafic lavas, which suggest modification of their source by high-Rb/Sr and high- $^{87}\text{Sr}/^{86}\text{Sr}$ materials (e.g. ancient continental crust or

terrigenous sediments). Accordingly, the different mantle domain beneath the Yanshan belt compared with the NCB interior is in accord with lithospheric mantle evolution in circumcratonic terranes, where subduction-related crustal recycling plays an important role in the refertilization of SCLM (e.g. Boyd 1989; Menzies 1989).

Geodynamic implications for Mesozoic tectonomagmatism

According to the above discussion, the Mesozoic Yanshan belt mafic lavas were derived from a heterogeneous SCLM that had been previously enriched in LILE and LREE. Although the Mesozoic mafic volcanism is subordinate when compared with the predominant intermediate–felsic magmatism, generation of these mafic magmas provides important constraints on the dynamics of melting within the SCLM and geodynamic models for lithospheric evolution through Mesozoic time.

Both numerical modelling and thermal considerations suggest that in the absence of plume activity, basaltic generation in continental settings is linked with either lithospheric extension or slab subduction (e.g. McKenzie & Bickle 1988; Arculus 1994; Kerr 1994; Hawkesworth *et al.* 1995; Hunter & Blake 1995; Macdonald *et al.* 2000; Fan *et al.* 2003). The predominant intermediate–felsic lavas and subordinate mafic rocks in the Yanshan belt are compositionally different from plume-related large igneous provinces, which mainly comprise basalts, thus precluding the role of plume impact. On one hand, the 240–250 Ma peak metamorphism from the Lesser Hinggan Mountain to the Xilin Gol metamorphic belt and the emplacement of Indo-Sinian alkaline complexes along the northern NCB marked the end of orogeny related to the subduction of the palaeo-Asian Ocean (e.g. Yan *et al.* 2000; Shi *et al.* 2003; Miao *et al.* 2004). An origin related to the palaeo-Asian Ocean subduction seems unsuitable for these mafic rocks. On the other hand, the occurrence of a series of accretionary prisms from Jurassic to Cenozoic time in the Japan arcs suggests the role of multistage oceanic slab subduction during the growth of the East Asian continent (e.g. Faure & Natal'in 1992; Taira 2001), such accretionary complexes are absent in the Yanshan belt and its surrounding regions. Palaeomagnetic surveys of the Pacific Ocean and the Eurasia continent have indicated that the westward subduction of the palaeo-Pacific Ocean began at *c.* 100 Ma (Engelbreton *et al.* 1985; Northrup *et al.* 1995). The Mesozoic (180–110 Ma) Yanshan belt mafic volcanism predates the westward Pacific subduction event. Similarly, an origin related to the palaeo-Pacific Ocean subduction is also inapplicable

to interpret the Mesozoic Yanshan belt mafic rocks. Accordingly, a multistage lithospheric extension model is envisaged to explain the basaltic generation in the Yanshan belt through Mesozoic time.

The Group 1 mafic volcanic rocks. The Group 1 mafic rocks in the Yanshan belt are sporadically distributed along the Xinglong–Kuancheng and Chicheng–Luanping faults, and crop out in small volumes (HBGMR 1989). Geochemical and geothermal considerations suggest that such small volumes of SCLM-derived mafic melts could be produced by either thermal perturbation or local lithospheric extension. Geometric surveys and thermal chronology of structural deformation identified a pre-180 Ma south-vergent thrust event prior to the eruption of the Nandaling Fm. basalts (Fig. 12a). Despite the controversy about the dynamics of this event (e.g. Wang 1996; Deng *et al.* 1999; Davis *et al.* 2001), the nearly east–west-trending lineation on the thrust faults suggests that their formation was related to a north–south-directed compressional stress field, either as a consequence of the collisional suturing of Palaeozoic Mongolian arcs against an Andean-style continental arc along the northern NCB (Shi *et al.* 2003; Miao *et al.* 2004), or as an expression of a back-arc, foreland fold and thrust belt of US Cordilleran type formed during southward subduction of the Mongolia–Okhotsk Ocean beneath the NCB (Fig. 12a; Davis *et al.* 2001). Subsequent extension in response to either post-collisional stress relaxation or lithospheric readjustment triggered asthenospheric upwelling and partial melting of the previously enriched sources to generate these mafic magmas (Fig. 12b).

The Group 2 basaltic lavas

In essence, the Group 2 volcanism in the northern NCB is characterized by extrusion of predominant intermediate–felsic lavas and minor basaltic rocks, such as the Tiaojiashan Fm., which is mainly composed of calc-alkaline andesites and dacites, with subordinate mafic rocks (e.g. Bao *et al.* 1995; Li *et al.* 2001). Extensive melting of crustal rocks requires a high heat supply as a result of either crustal thickening or basaltic underplating. Unlike syntectonic peraluminous intermediate–felsic rocks, which can be produced through melting of middle–upper crustal rocks by means of crustal thickening for accumulation of high heat productivity radioactive elements (e.g. Thompson 1982; Ellis & Thompson 1986), the Group 2 intermediate–felsic lavas in this region mainly have metaluminous to calc-alkaline affinities, and were derived from the lower crust and/or

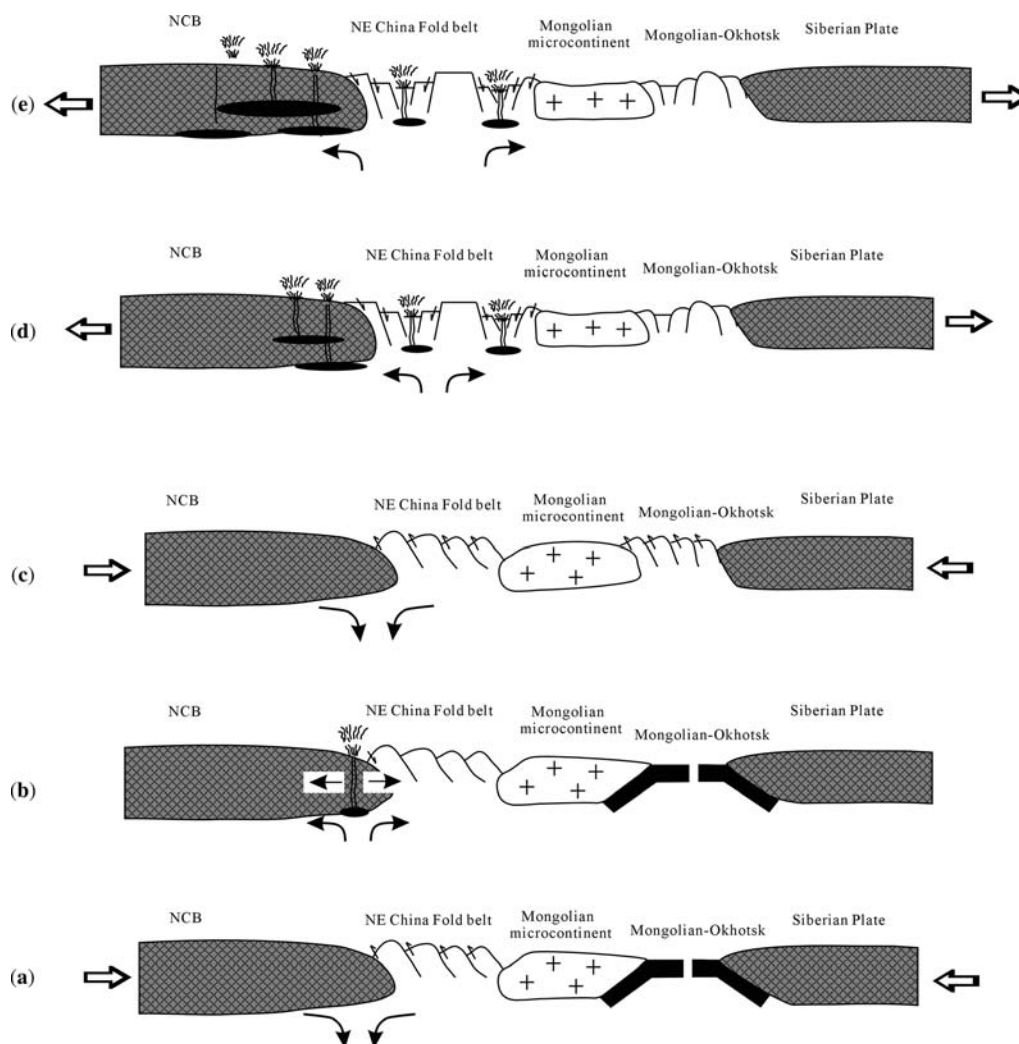


Fig. 12. A schematic illustration of the Mesozoic tectonic evolution of the Yanshan belt. (a) At *c.* ~240 Ma, the northern NCB was involved in the collision between the Mongolian Block and NCB (Shi *et al.* 2003; Miao *et al.* 2004); resulting in a pre-180 Ma contractional deformation event (Zhao *et al.* 1990; Davis *et al.* 2001). (b) At *c.* 180 Ma, local extension in response to post-compressional stress relaxation or lithospheric readjustment along the pre-existing major faults (e.g. the GXPF), resulting in the eruption of sporadic Nandaling Fm. basalts (e.g. Bao *et al.* 1995; Li *et al.* 2004). (c) In the Middle Jurassic, collision between the North China–Mongolian Block and the Siberian plate (e.g. Zhao *et al.* 1990) resulted in the north–south directed contractional deformation in the northern NCB. (d) In the Late Jurassic, post-collisional extension and large-scale volcanic eruption took place in the NE China Fold belt (Fan *et al.* 2003) and the northern NCB (Group 2), and gave rise to syntectonic kilometre-scale sediment deposition (e.g. Davis *et al.* 1998, 2001; He *et al.* 1998; Zheng *et al.* 1999; Cui *et al.* 2002). (e) In the Early Cretaceous, the Group 3 volcanic rocks were extruded under an extensional regime in response to lateral escape tectonics related to surrounding plate interactions.

underplated mafic cumulates (e.g. Li *et al.* 2001). This required significant lithospheric extension to trigger basaltic underplating to reheat the lower–middle crust (Bergantz 1989), and the scarce exposure of basaltic lavas might be a result of mafic cumulates emplaced at crustal levels, as

indicated by magmatic granulite-facies rocks at Hannuoba (Fan *et al.* 1998; Zhang *et al.* 1998; Zhou *et al.* 2002; Wilde *et al.* 2003). Because the collision between the North China–Mongolian Block and the Siberian plate was terminated by the end of the middle Jurassic (e.g. Zhao *et al.*

1990), contractional deformation took place along the Yanshan–Yinshan belt (e.g. Zhang & Song 1997; Zheng *et al.* 1999; Davis *et al.* 2001), for example, giving rise to the Chengde–Xinglong thrust and Shihetang nappes (Fig. 12c). Thermal decay and decrease in the amount of lithospheric extension triggered small-scale melting of the mantle source to produce shoshonitic magmas in the Houcheng Fm. Both the structural deformation styles and the metaluminous affinities of magmatic activity in this region are essentially similar to those in a post-collisional setting (e.g. Turner *et al.* 1996; Miller *et al.* 1999; Fan *et al.* 2003). In combination with the almost east–west-trending distribution of the volcanic sequences and structural alignment of the sedimentary basins, the lithospheric extension also had a north–south-trend (Fig. 12d), either as a consequence of thermal perturbation caused by the far-field effect from the collision of the two continents or as an expression of post-collisional collapse.

The Group 3 basalts

By the end of the Jurassic or at the beginning of the Cretaceous, there existed a regional angular unconformity between the Houcheng or Tuchengzi Fm. sediments and the Zhangjiakou or Donglingtai Fm. felsic lavas. The cause of this tectonic event is still unclear; it may have been a result of gravitational collapse of the Yanshan belt or a consequence of strike-slip extension induced by the northward motion of the palaeo-Pacific Ocean. The subsequent lithospheric extension reached its maximum, accompanied by voluminous eruption of magmas (the Zhangjiakou and Huajiying Fms. in the Jibei region, the Yixian Fm. in the Liaoxi region, and the Donglingtai and Donglanggou Fms. in the Xishan area and within the NCB (Fig. 12e; e.g. Bao *et al.* 1995; Chen *et al.* 1997; Zhou *et al.* 2001; Cui *et al.* 2002; Guo *et al.* 2003). During this period, the volcanism was also strongest throughout eastern China, forming a NE–SW-trending magmatic belt thousands of kilometres in extent. In recent years, structural studies of late Mesozoic deformation in eastern China have indicated a prevalent extensional regime associated with strike-slip displacement and lateral extrusion in response to surrounding plate interactions (Xu *et al.* 1987; Yin & Nie 1993; Hacker *et al.* 2000; Ratschbacher *et al.* 2000; Wang *et al.* 2003). For instance, the NCB was subjected to southward and northeastward compression from the Siberian Plate and the Lhasa–Qiangtang Block, respectively (e.g. Menzies *et al.* 1993; Yin & Nie 1993; Hacker *et al.* 2000; Ratschbacher *et al.* 2000; Guo *et al.* 2003; Wang *et al.* 2003). These two indentors led to NE-directed lateral escape of the lithosphere.

Simultaneously, the rapid northward movement of the palaeo-Pacific Ocean and the induced large-scale strike-slip displacement of lithosphere-scale faults (Engelbreton *et al.* 1985; Northrup *et al.* 1995), such as the Tan-Lu wrench fault system (Xu *et al.* 1987), provided a focus for strike-slip deformation along the East Asian continental margin. The resultant force was favourable for rapid dispersion of extrusive materials, the development of extensional tectonics, and extensive magmatism in the Yanshan belt and its surrounding areas.

Conclusions

The Mesozoic Yanshan belt mafic lavas, characterized by significant LILE and LREE enrichment but Nb–Ta and Th–U depletion, and moderately radiogenic Sr and unradiogenic Nd isotopic compositions, were derived from a heterogeneous lithospheric mantle that had been previously enriched in LILE and LREE, probably as a consequence of recycling of the ancient NCB lower crustal materials related to the palaeo-Asian Ocean subduction. The high Ti₈ and Fe₈, and low Si₈ relative to the late Mesozoic NCB interior mafic rocks indicate that the Yanshan belt mafic lavas were probably derived from a relatively fertile source, different from the chemically refractory, lithospheric mantle within the NCB. Such a difference is in accord with mantle evolution beneath circumcratonic terranes, where recycled crustal materials play an important role in refertilization of mantle lithosphere. Combining the Mesozoic magma petrogenesis with the crust–lithosphere deformation history, the multistage intracontinental tectonomagmatic episodes occurring in the Yanshan belt were responses to surrounding plate interactions with the lithospheric evolution of the NCB continental margins.

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