

Sources and Petrogenesis of Late Triassic Dolerite Dikes in the Liaodong Peninsula: Implications for Post-collisional Lithosphere Thinning of the Eastern North China Craton

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A combination of major and trace element, whole-rock Sr, Nd and Hf isotope, and zircon U–Pb isotopic data are reported for a suite of dolerite dikes from the Liaodong Peninsula in the northeastern North China Craton. The study aimed to investigate the source, petrogenesis and tectonic setting of the dikes. Sensitive high-resolution ion microprobe U–Pb zircon analyses yield a Late Triassic emplacement age of ~213 Ma for these dikes, post-dating the collision between the North China and Yangtze cratons and consequent ultrahigh-pressure metamorphism. Three geochemical groups of dikes have been identified in the Liaodong Peninsula based on their geochemical and Sr–Nd–Hf isotope characteristics. Group 1 dikes are tholeiitic, with high TiO₂ and total Fe₂O₃ and low MgO contents, absent to weak negative Nb and Ta anomalies, variable (⁸⁷Sr/⁸⁶Sr)_i (0.7060–0.7153), ε_{Nd}(t) (–0.8 to –6.5) and ε_{Hf}(t) (–2.7 to –7.8) values, and negative Δε_{Hf}(t) (–1.1 to –7.8). They are inferred to be derived from partial melting of a relatively fertile asthenospheric mantle in the spinel stability field, with some upper crustal assimilation and fractional crystallization. Group 2 dikes have geochemical features of high-Mg andesites with (⁸⁷Sr/⁸⁶Sr)_i values of 0.7063–0.7072, and negative ε_{Nd}(t) (–3.0 to –9.5) and ε_{Hf}(t) (–3.2 to –10.1) values, and may have originated as melts of foundered lower crust, with subsequent interaction with mantle peridotite. Group 3 dikes are shoshonitic in composition with relatively low (⁸⁷Sr/⁸⁶Sr)_i values (0.7061–0.7063), and negative ε_{Nd}(t) (–13.2 to –13.4) and ε_{Hf}(t) (–11.0 to –11.5) values, and were derived by partial melting of an ancient, re-enriched,

refractory lithospheric mantle in the garnet stability field. The geochemical and geochronological data presented here indicate that Late Triassic magmatism occurred in an extensional setting, most probably related to post-orogenic lithospheric delamination.

KEY WORDS: mafic dike; asthenospheric mantle; lithospheric mantle; delamination; North China Craton

INTRODUCTION

The tectonic evolution of orogenic belts is typically marked by changes in the composition of the associated magmatism (Harris *et al.*, 1986). Post-collisional magmatism is one of the common features of many orogens around the world, and may indicate that the orogen is in the process of collapsing (Dewey, 1988). Petrogenetic studies of post-collisional magmatism not only provide constraints on the geodynamic processes responsible for the cessation of collision and onset of extensional collapse (Bonin *et al.*, 1998), but also reveal changes in magma source regions associated with such processes (Turner *et al.*, 1992, 1996; Kay & Kay, 1993; Bonin *et al.*, 1998). Thus, the geochemical characteristics of post-collisional magmatism allow the evaluation of its mantle source and provide constraints on the cessation of collision and onset of extensional collapse.

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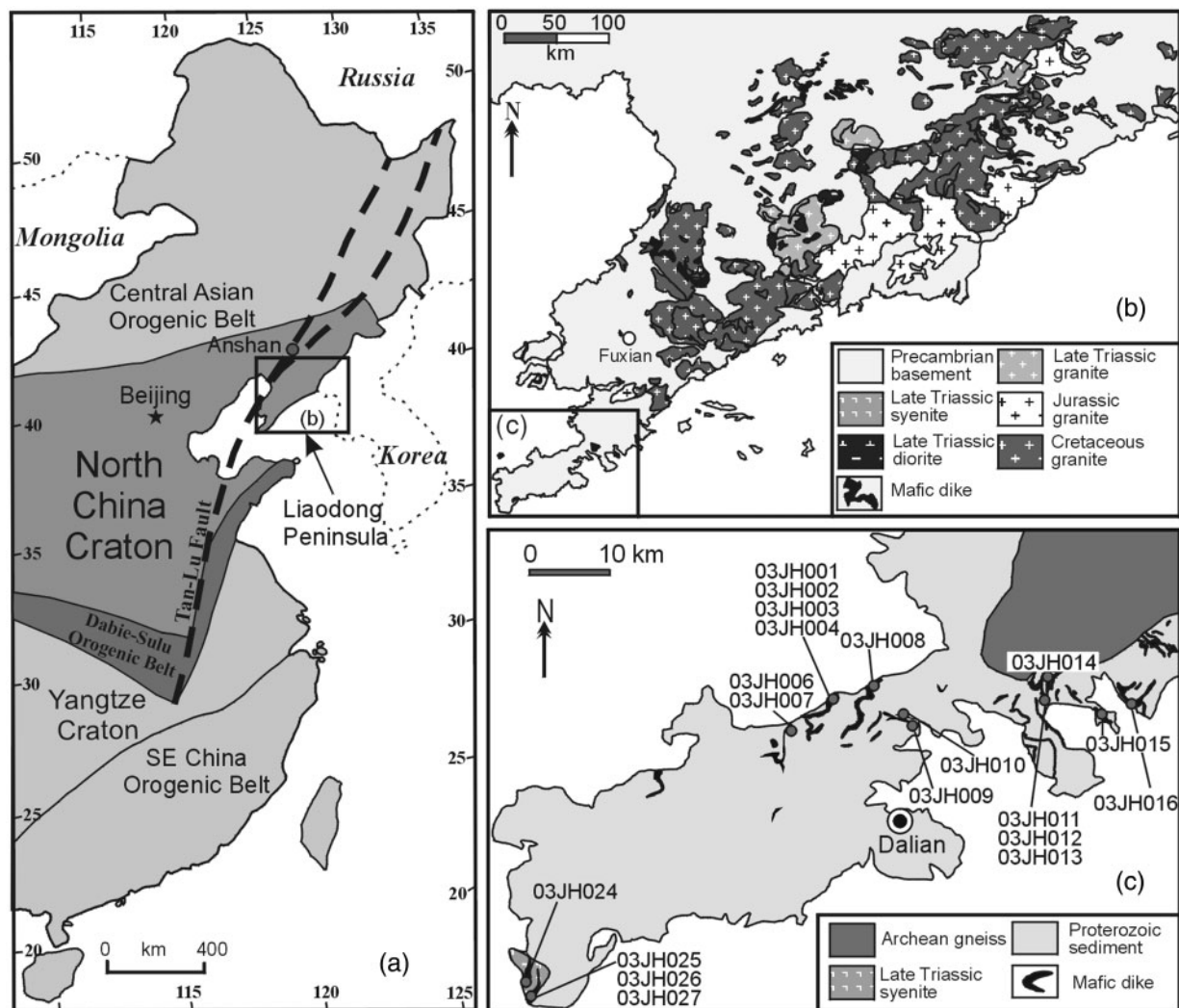


Fig. 1. (a) Simplified geological map of eastern China, showing major tectonic units (modified after Wang & Mo, 1996); (b) geological map showing distribution of Mesozoic magmatism in the Liaodong Peninsula (BGMRLNP, 1989); (c) distribution of mafic dikes in the Liaodong Peninsula, showing sample locations.

The Dabie–Sulu orogen in central China was formed by collision between the North China Craton (NCC) and Yangtze Craton (YC), and is known to contain the largest distribution of ultrahigh-pressure (UHP) metamorphic rocks in the world (Fig. 1a; Cong, 1996; Hacker *et al.*, 1998; Liu *et al.*, 2004; Wan *et al.*, 2005), which were formed by deep subduction (over ~ 200 km, Ye *et al.*, 2000) in the Early–Middle Triassic and exhumation to mid-crustal levels by the Late Triassic (Liu *et al.*, 2004; Wan *et al.*, 2005). Post-collisional magmatism is weakly developed in the Dabie–Sulu UHP orogenic belt, and only a single intrusion, the Jiazishan complex with an age of 215–200 Ma, has been identified in the Sulu part of the belt (Chen *et al.*, 2003; Guo *et al.*, 2005; Yang *et al.*, 2005). However, Late Triassic magmatism consisting of mafic

dikes, diorites, syenites and monzogranites with mafic enclaves has been identified in the Liaodong Peninsula of the northeastern NCC (Yang *et al.*, 2004a; Wu *et al.*, 2005a; Yang *et al.*, 2007a), located to the north of the Sulu UHP orogen (Fig. 1a and b).

Mafic dike swarms are a common expression of mantle-derived magma generation associated with extensional tectonic regimes in post-collisional or intraplate extensional settings (e.g. Rock, 1991). They can thus provide important information for understanding not only the mantle source of the magmas, but also the tectonic evolution of the orogenic belt and adjacent regions (Gorring *et al.*, 2001, 2003). In this paper, we report zircon U–Pb ages, major and trace element geochemistry, and Sr–Nd–Hf isotopic compositions of mafic dikes from the southern Liaodong

Peninsula to: (1) document the geochemical characteristics of these rocks; (2) investigate their mantle sources and petrogenesis; (3) interpret the evolution of lithospheric mantle beneath the eastern NCC; (4) evaluate the tectonic implications for the eastern NCC during the Late Triassic.

GEOLOGICAL SETTING

East China is composed of the Central Asian Orogenic Belt (CAOB) in the north, the NCC in the centre and the Yangtze Craton in the south (Fig. 1a; Wang & Mo, 1996). The Dabie–Sulu orogenic belt in east-central China (Fig. 1a) marks the collision zone between the North China and Yangtze cratons (Cong, 1996; Wang & Mo, 1996). Deep subduction of the Yangtze continental crust to >120 km depth is evident by the occurrence of micro-diamond in eclogites (Xu *et al.*, 1992); exhumation of even deeper rocks from >200 km depth was deduced from mineral exsolution relations (Ye *et al.*, 2000). Detailed zircon sensitive high-resolution ion microprobe (SHRIMP) U–Pb data and inferred *P–T* paths indicate that the protoliths of the UHP metamorphic rocks were subducted to mantle depths in the Early–Middle Triassic (244–226 Ma) and exhumed to mid-crustal levels by the Late Triassic (221–218 Ma) (Liu *et al.*, 2004; Wan *et al.*, 2005).

The Liaodong Peninsula is located in the northeastern segment of the NCC, to the north of the Sulu belt (Fig. 1a). It consists of Early Archean to Paleoproterozoic basement rocks overlain by unmetamorphosed Mesoproterozoic to Cenozoic cover. The Late Archean basement rocks consist of ~2.5 Ga diorite–tonalite–granodiorite suites (Lu *et al.*, 2004) that were deformed during the Paleoproterozoic (Yin & Nie, 1996) and Early Cretaceous (120–110 Ma) (Yang *et al.*, 2004b, 2007b). Paleoproterozoic rocks (the Liaohe Group) unconformably overlie the Late Archean rocks, and were deposited and then metamorphosed during a 1.9–1.85 Ga orogenic event (Lu *et al.*, 2004; Luo *et al.*, 2004). Subsequently, the Liaodong Peninsula was covered by thick sequences of Meso- to Neoproterozoic and Paleozoic sediments. Before the Mesozoic, igneous activity was weak, indicating that the Liaodong Peninsula was tectonically stable.

Mesozoic intrusive rocks are widely distributed in the Liaodong Peninsula and cover an area of ~20 000 km² (Fig. 1b); magmatism mostly occurred in the Late Jurassic (173–150 Ma) and Early Cretaceous (135–110 Ma) (Yang *et al.*, 2004c, 2006a, 2007c; Wu *et al.*, 2005b, 2005c). However, minor Triassic magmatism (230–210 Ma) has been identified (Wu *et al.*, 2005a; Yang *et al.*, 2007a), consisting of mafic dikes, nepheline syenites, syenites, diorites and monzogranites with mafic enclaves. Many mafic dikes are exposed in the Dalian area, in the southern Liaodong Peninsula (Fig. 1c).

PETROLOGY OF THE MAFIC DIKES

The mafic dikes intrude Neoproterozoic sandstones and limestones and Middle Triassic syenites; some of these dikes were also emplaced during the Late Mesozoic (Wang *et al.*, 2000). The dikes are tens of meters to 300 m in width and several hundred meters to several kilometers in length. They have a doleritic composition, with a medium- to fine-grained ophitic texture. The main minerals are plagioclase (40–50%), clinopyroxene (45–50%), K-feldspar (~5%), and minor quartz and biotite. Accessory minerals include magnetite, ilmenite, zircon, apatite and titanite. The detailed mineralogy of all samples is listed in Table 1.

ANALYTICAL METHODS

Zircon U–Pb dating

Two dike samples (03JH011 and 03JH025) from the Liaodong Peninsula were chosen for zircon U–Pb dating. Samples of fresh rock (about 25 kg) were crushed and the heavy mineral fraction, including zircon, was extracted using standard techniques including heavy liquid separation. Zircon was extracted from each crushed-rock concentrate by hand-picking under a binocular microscope. The zircon grains were placed on a mount, sectioned and polished. The mounts were carbon coated for cathodoluminescence (CL) imaging and gold coated for the ion microprobe analyses. Measurements of U, Th, and Pb (Table 1) were conducted using the SHRIMP II ion microprobe at the Beijing SHRIMP Laboratory. U–Th–Pb ratios and absolute abundances were determined relative to the SL13 standard zircon (²⁰⁶Pb/²³⁸U = 0.092821 corresponding to 572 Ma; 238 ppm ²³⁸U; Claoué-Long *et al.*, 1995). Analyses of the TEM zircon standard were interspersed with those of unknown grains, to monitor analytical conditions throughout the session. The machine operating conditions were similar to those described by Nelson (1997). Measured compositions were corrected for common Pb assuming the composition of Broken Hill lead, and the data were recalculated on the basis of the measured non-radiogenic ²⁰⁴Pb content. The SQUID 1.0 and ISOPLOT 3.0 software of Ludwig (2003) were used for data processing. Uncertainties on individual analyses in data tables are reported at the 1σ level. The ²⁰⁶Pb/²³⁸U ages are considered the most reliable for Phanerozoic zircons such as these, as the zircons are concordant and the low count rates on ²⁰⁷Pb result in large statistical uncertainties, making the ²⁰⁷Pb/²⁰⁶Pb and ²⁰⁷Pb/²³⁵U ratios a less sensitive measure of age for younger zircons (Compston *et al.*, 1992). Weighted mean ages for pooled ²⁰⁶Pb/²³⁸U analyses are quoted at the 95% confidence level, except where noted. The zircon U_{Pb} data are presented in Table 2 and shown in Fig. 2.

Table 1: Petrography and mineral assemblages of the dikes of the Liaodong Peninsula

Sample no.	Group	Latitude, longitude	Locality	SiO ₂ (wt%)	Mg-no.	Texture	Mineral assemblage
03JH001	1	N39°03'14.4", E121°32'45.8"	Qipanmo	48.57	37.9	Medium-grained, ophitic texture	Cpx + Pl + Fe-Ti + Kf + Ap + Zr
03JH002	1	N39°03'14.4", E121°32'45.8"	Qipanmo	49.64	34.1	Fine-grained, ophitic texture	Cpx + Pl + Fe-Ti + Tit
03JH003	1	N39°03'14.4", E121°32'45.8"	Qipanmo	49.82	35.4	Fine- to medium-grained, ophitic texture	Cpx + Pl + Fe-Ti + Tit
03JH004	1	N39°03'14.4", E121°32'45.8"	Qipanmo	49.43	35.3	Fine- to medium-grained, ophitic texture	Cpx + Pl + Fe-Ti + Kf + Tit
03JH006	1	N39°01'55.6", E121°30'26.5"	Xiajiahe	47.46	35.8	Fine- to medium-grained, ophitic and porphyritic texture	Phenocryst: Cpx + Pl + Ol Groundmass: Cpx + Pl + Ol + Fe-Ti + Tit
03JH007	1	N39°01'55.6", E121°30'26.5"	Xiajiahe	55.08	20.1	Medium-grained, ophitic texture	Cpx + Pl + Fe-Ti + Ap + Zr
03JH008	1	N39°04'07.1", E121°35'58.1"	Dalashufang	49.21	41.5	Fine-grained	Cpx + Pl + Fe-Ti
03JH009	1	N39°00'37.7", E121°39'06.8"	Qianyancun	49.25	43.4	Medium-grained, ophitic texture	Cpx + Pl + Fe-Ti + Tit + Ap + Zr
03JH011	1	N39°04'59.1", E121°47'46.7"	Mulancun	47.87	45.3	Medium-grained, ophitic texture	Cpx + Pl + Fe-Ti + Tit + Ap + Zr
03JH012	1	N39°04'59.1", E121°47'46.7"	Mulancun	47.45	46.5	Medium-grained, ophitic texture	Cpx + Pl + Fe-Ti + Tit + Ap
03JH015	1	N39°02'27.5", E121°53'50.9"	Xiaoyaowan	47.13	43.2	Medium-grained, ophitic texture	Cpx + Pl + Fe-Ti + Tit + Ap + Zr
03JH016	1	N39°03'17.2", E121°55'23.5"	Xiaoyaowan	49.18	47.5	Medium-grained, ophitic texture	Cpx + Pl + Fe-Ti + Tit + Ap
03JH013	2	N39°04'59.1", E121°47'46.7"	Mulancun	53.08	69.4	Fine-grained	Cpx + Pl + Kf + Mag
03JH024	2	N38°45'41.6", E121°07'42.3"	Yujiaacun	55.58	69.2	Fine-grained	Cpx + Pl + Kf + Qz + Mag
03JH027	2	N38°45'21.6", E121°07'44.3"	Yinjiacun	55.26	65.9	Fine-grained	Cpx + Pl + Kf + Qz + Mag
03JH025	3	N38°45'21.6", E121°07'44.3"	Yinjiacun	49.58	57.6	Medium-grained, ophitic texture	Cpx + Pl + Kf + Bi + Ap + Zr
03JH026	3	N38°45'21.6", E121°07'44.3"	Yinjiacun	51.88	58.1	Medium-grained, ophitic texture	Cpx + Pl + Kf + Bi + Ap + Zr

Ap, apatite; Cpx, clinopyroxene; Fe-Ti, Fe-Ti oxides; Kf, K-feldspar; Mag, magnetite; Ol, olivine; Bi, biotite; Pl, plagioclase; Qz, quartz; Tit, titanite; Zr, zircon.

Major and trace elements

After petrographic examination, 17 of 19 samples from the southern part of the Liaodong Peninsula (Table 2 and Fig. 1c) are fresh and were selected, crushed and powdered in an agate mill for geochemical analysis. Elemental analyses were conducted in the Department of Geology, Northwest University in Xi'an, China. Major elements were determined by X-ray fluorescence (XRF), with analytical uncertainties ranging from 1 to 3%. Trace element concentrations were determined by inductively coupled plasma mass spectrometry (ICP-MS) using an Agilent 7500a system. For trace element determination, about 50 mg of crushed whole-rock powder was dissolved for about 7 days at $\sim 100^\circ\text{C}$ using HF-HNO_3 (10:1) mixtures in screw-top Teflon beakers, followed by evaporation to dryness. The material was dissolved in 7N HNO_3 and taken to incipient dryness again, and then was re-dissolved in 2% HNO_3 to a sample/solution weight ratio of 1:1000. The analytical errors vary from 5 to 10% depending on the concentration of any given element. An internal standard was used for monitoring drift during analysis; further details have been given by Gao *et al.* (2002).

Nd, Sr and Hf isotopes

Rock powders for Nd–Sr isotopic analysis were dissolved in Teflon bombs after being spiked with ^{84}Sr , ^{87}Rb , ^{150}Nd , and ^{147}Sm enriched isotope tracers prior to $\text{HF} + \text{HNO}_3$ (in a ratio of 2:1) dissolution. Rubidium, Sr, Sm, and Nd were separated using conventional ion exchange procedures as described by Yang *et al.* (2004d) and measured using a Finnigan MAT 262 multi-collector mass spectrometer at the Institute of Geology and Geophysics, Chinese Academy of Sciences. Procedural blanks were <100 pg for Sm and Nd and <500 pg for Rb and Sr. $^{143}\text{Nd}/^{144}\text{Nd}$ values were corrected for mass fractionation by normalization to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were 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 analytical errors for Rb, Sr, Sm and Nd contents are better than 2%, distinct from those determined by the ICP-MS technique, which resulted in differences in Rb, Sr, Sm and Nd concentrations between the isotope dilution (ID) and ICP-MS methods. The measured values for the La Jolla and BCR-1 Nd standards and NBS-607 Sr standard were $^{143}\text{Nd}/^{144}\text{Nd} = 0.511853 \pm 7$ ($2\sigma_n$, $n=3$) and 0.512604 ± 7 ($2\sigma_n$, $n=3$) and $^{87}\text{Sr}/^{86}\text{Sr} = 1.20042 \pm 2$ ($2\sigma_n$, $n=12$) during the period of data acquisition.

Hf isotopic analyses were conducted in the multicollector (MC)-ICP-MS Laboratory, Institute of Geology and Geophysics, Chinese Academy of Sciences (Beijing), using a ThermoElectron Neptune MC-ICP-MS system. Sample powder (100 mg) was dissolved in sealed Teflon bombs. Separation of Hf was performed using a routine two-column ion exchange technique which includes: (1)

group separation of high field strength elements (HFSE) through a cation exchange column (1 cm $\times$ 8 cm, packed with Bio-Rad AG50X8, 200–400 mesh resin); (2) purification of Hf through a second exchange column packed with Ln resin. $^{176}\text{Hf}/^{177}\text{Hf}$ measurements were normalized to $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$. During the period of data acquisition, standard BHVO-1 was also processed for Hf isotopes, and gave a ratio of 0.283105 ± 6 ($2\sigma_m$) for $^{176}\text{Hf}/^{177}\text{Hf}$, agreeing with the recommended value (0.283100 ± 3 , Weis *et al.*, 2005).

RESULTS

Geochronology

Zircons from mafic dike sample 03JH025 show oscillatory zoning, typical of igneous crystallization, and have light margins in CL images (Fig. 2a). Eleven analyses yield ages between 222 ± 4 and 204 ± 2 Ma (1σ) and form a coherent group with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 213 ± 5 Ma (2σ , $\text{MSWD} = 1.2$) (Fig. 2a). However, zircons from sample 03JH011, previously reported in Yang *et al.* (2004a), are relatively homogeneous and grey in CL, although one grain has oscillatory zoning and a large apatite inclusion in the core that appears white in the CL image (Fig. 2b). This grain yields a $^{206}\text{Pb}/^{238}\text{U}$ age of 211 ± 2 Ma, whereas the other zircon grains give $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1.1–0.8 Ga (Fig. 2b) and are interpreted either to result from wall-rock contamination of the mafic magma during emplacement or to be inherited from the source rock. The Late Triassic age (~ 213 Ma) is consistent with the previous result [213.0 ± 1.5 Ma, zircon thermal ionization mass spectrometry (TIMS) U–Pb age] of Wang *et al.* (2000) and the field observation that some dikes intrude deformed Triassic syenites with an age of 220 ± 2 Ma (zircon LA-ICP-MS U–Pb age, Wu *et al.*, 2005a). Thus, the age of 213 Ma represents the emplacement age of the dolerites in the Liaodong Peninsula.

Geochemistry

Full major and trace element analyses of the Liaodong dikes are presented in Table 3. Rubidium, Sr, Sm and Nd concentrations, $^{143}\text{Nd}/^{144}\text{Nd}$, $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ ratios, and Nd and Hf model ages for these mafic dikes are listed in Table 4 and shown in Fig. 7. The $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios, $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ values have been calculated at 213 Ma on the basis of the U–Pb zircon dating. $\Delta\epsilon_{\text{Hf}}(t)$ is defined as $\epsilon_{\text{Hf}}(t) = 1.33\epsilon_{\text{Nd}}(t) + 3.19$ such that a sample with positive $\Delta\epsilon_{\text{Hf}}(t)$ lies above and a sample with negative $\Delta\epsilon_{\text{Hf}}(t)$ lies below the mantle array of Vervoort *et al.* (1999).

The samples exhibit significant variations in major and trace element and Sr–Nd–Hf isotopic compositions (Tables 3 and 4). The dikes are subalkaline to alkaline and range in composition from basalt to basaltic andesite and basaltic trachyandesite (Fig. 3a). On the basis of their

Table 2: Zircon SHRIMP U–Pb data for Group 3 dike (03JH025) and Group 1 dike (03JH011) from the Liaodong Peninsula of northeastern North China Craton

Spot	²⁰⁶ Pb _c (%)	U (ppm)	Th (ppm)	Th/U	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ (%)	²⁰⁷ Pb*/ ²⁰⁶ Pb*	1σ (%)	²⁰⁷ Pb*/ ²³⁵ U	1σ (%)	²⁰⁶ Pb*/ ²³⁸ U	1σ (%)	²⁰⁶ Pb/ ²³⁸ U	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ
03JH025-1	0.48	439	1263	2.97	0.0531	2.7	0.0493	4.3	0.2183	4.4	0.0321	0.9	204	2	200	9	160	100
03JH025-2	2.03	268	338	1.30	0.0659	3.3	0.0496	13	0.2290	13	0.0335	1.4	213	3	209	27	177	300
03JH025-3	5.17	130	157	1.25	0.0766	5.3	0.0340	31	0.1580	31	0.0333	2.1	211	4	149	46	–752	870
03JH025-4	3.63	119	92	0.80	0.0746	8.9	0.0454	22	0.2190	22	0.0351	1.9	222	4	201	44	–37	520
03JH025-5	3.14	128	143	1.16	0.0713	7.4	0.0460	22	0.2110	22	0.0332	2.0	210	4	194	43	2	540
03JH025-6	1.50	229	286	1.29	0.0624	5.6	0.0505	11	0.2350	11	0.0338	1.7	215	4	214	24	216	260
03JH025-7	0.00	213	256	1.24	0.0606	3.5	0.0606	3.5	0.2870	3.7	0.0344	1.2	218	3	256	9	627	76
03JH025-8	2.40	133	166	1.29	0.0664	5.7	0.0472	18	0.2160	18	0.0332	2.0	211	4	199	36	57	430
03JH025-9	3.93	52	41	0.82	0.0872	7.7	0.0560	38	0.2520	9.0	0.0336	1.8	213	8	228	21	451	850
03JH025-10	0.57	269	193	0.74	0.0576	3.2	0.0530	5.4	0.2400	5.7	0.0328	1.9	208	4	218	12	331	120
03JH025-11	0.33	483	1293	2.76	0.0553	2.4	0.0526	2.8	0.2520	2.9	0.0347	0.8	220	2	228	7	312	63
03JH011-01	0.36	722	988	1.41	0.0707	1.3	0.0677	1.8	1.291	1.9	0.1382	0.6	835	5	842	16	861	37
03JH011-02	0.97	778	236	0.31	0.0570	3.1	0.0493	5.9	0.226	5.9	0.0333	0.8	211	2	207	4	161	138
03JH011-03	0.10	903	1223	1.40	0.0704	0.8	0.0696	1.0	1.357	1.2	0.1414	0.6	852	5	871	17	917	20
03JH011-04	0.46	546	691	1.31	0.0703	1.1	0.0665	1.8	1.377	2.1	0.1502	1.1	902	9	879	17	821	38
03JH011-05	0.32	929	1510	1.68	0.0718	0.8	0.0691	1.5	1.428	1.6	0.1499	0.5	900	4	901	17	902	32
03JH011-06	0.16	1637	3566	2.25	0.0700	0.6	0.0687	0.9	1.384	0.9	0.1461	0.4	879	3	882	17	890	18
03JH011-07	0.17	650	831	1.32	0.0697	1.0	0.0683	1.3	1.415	1.4	0.1502	0.5	902	4	895	17	878	26
03JH011-08	0.60	284	48	0.18	0.0821	1.2	0.0772	1.9	1.941	2.1	0.1825	0.7	1081	7	1095	21	1125	38
03JH011-09	0.09	1604	3274	2.11	0.0704	0.6	0.0697	0.7	1.460	0.8	0.1520	0.3	912	2	914	17	919	14
03JH011-10	0.16	1071	1972	1.90	0.0697	1.1	0.0684	1.3	1.257	1.4	0.1332	0.4	806	3	826	16	881	26
03JH011-11	0.14	992	1588	1.65	0.0714	0.8	0.0703	0.9	1.422	1.0	0.1467	0.4	883	3	898	17	937	19

Errors are 1σ; Pb_c and Pb* indicate the common and radiogenic portions, respectively. Uncertainty in standard calibration was 0.35% (not included in above errors). Common Pb corrected using measured ²⁰⁴Pb. Data for sample 03JH011 are from Yang *et al.* (2004a).

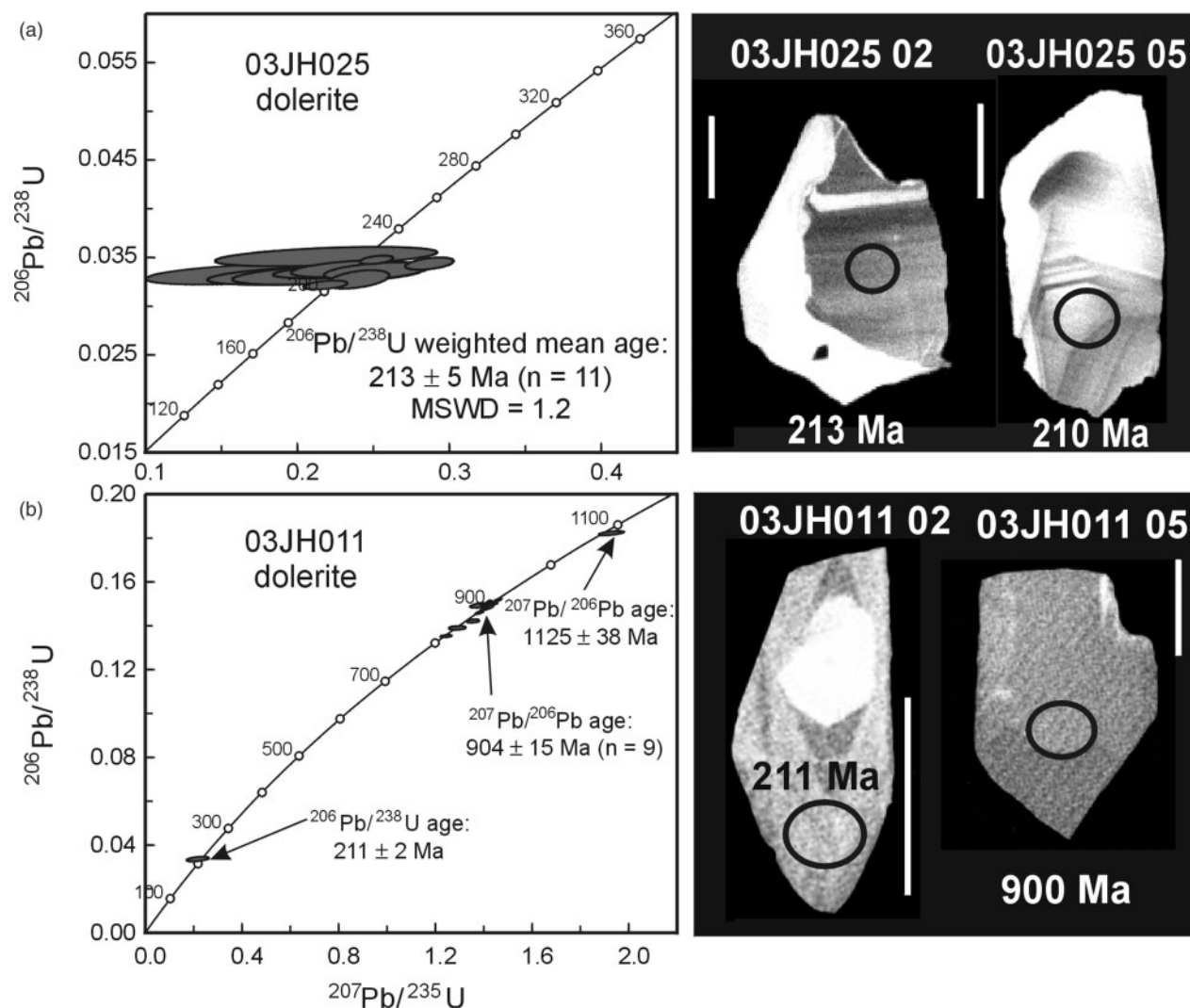


Fig. 2. SHRIMP U-Pb zircon concordia diagrams for (a) Group 3 dike (03JH025) and (b) Group 1 dike (03JH011) from the Liaodong Peninsula. Cathodoluminescence (CL) images of representative zircons from dike samples are shown as insets in the figures. Circles indicate location of SHRIMP U-Pb analysis sites; their ages are given for each grain. The scale bars all represent 50 μm . The data for 03JH011 are from Yang *et al.* (2004a).

distinct petrography (Table 1), geochemistry (Table 3) and Sr-Nd-Hf isotopic compositions (Table 4), three groups of dikes can be identified.

Group 1

Group 1 dikes, mainly composed of clinopyroxene, plagioclase and Fe-Ti oxides, are basic to intermediate in composition (SiO_2 47.2–55.1 wt%) and belong to the tholeiitic series (Fig. 3a and b), with high abundances of total Fe_2O_3 (13.4–17.6 wt%), TiO_2 (2.4–4.2 wt%) and CaO (5.7–10.0 wt%) and low concentrations of Al_2O_3 (11.8–13.7 wt%), K_2O (0.5–2.0 wt%), Cr (1.1–101 ppm) and Ni (1.5–73.6 ppm) (Table 3; Figs 3c and 4). They have low MgO (2.01–6.07 wt%) and mg-numbers [where

$\text{mg-number} = 100 \times \text{Mg}/(\text{Mg} + \text{Fe}^{2+}) = 20.1\text{--}47.5$] (Fig. 3d). Group 1 dikes are light rare earth element (LREE) enriched with $(\text{La}/\text{Yb})_{\text{CN}}$ (subscript 'CN' refers to values normalized to chondrite) ranging from 3.0 to 6.6 and LREE contents up to 118 times chondrite (Fig. 5a). All samples have relatively flat middle REE (MREE) to heavy REE (HREE) chondrite-normalized REE patterns with $(\text{Dy}/\text{Yb})_{\text{CN}}$ values of 1.2–1.4. In primitive mantle (PM)-normalized trace element patterns (Fig. 6a), they are enriched in large ion lithophile elements (LILE), including Rb, Th and U, and LREE, but with variable negative Ba and Sr anomalies. They are also enriched in HFSE and lack negative Nb, Ta, Zr and Hf anomalies.

Table 3: Major (wt%) and trace (ppm) element data of mafic dikes from the Liaodong Peninsula of northeastern North China Craton

Location:	N39°03'14", E121°32'46"				N39°01'56", E121°30'27"		N39°04'07", E121°35'58"	N39°00'38", E121°39'07"
Group:	1	1	1	1	1	1	1	1
Sample:	03JH001	03JH002	03JH003	03JH004	03JH006	03JH007	03JH008	03JH009
<i>wt%</i>								
SiO ₂	48.57	49.64	49.82	49.43	47.46	55.08	49.21	49.25
TiO ₂	3.52	3.57	3.47	3.45	4.18	2.24	2.82	2.63
Al ₂ O ₃	12.55	12.42	12.23	12.00	11.97	11.79	12.80	12.85
TFe ₂ O ₃	16.02	16.22	16.02	16.11	17.57	15.96	15.33	15.60
MnO	0.21	0.24	0.22	0.21	0.24	0.18	0.21	0.22
MgO	4.89	4.20	4.39	4.39	4.89	2.01	5.44	5.97
CaO	7.61	6.37	7.41	7.72	8.03	5.68	8.16	8.87
Na ₂ O	2.40	2.70	2.65	2.72	2.39	2.72	2.94	2.22
K ₂ O	1.52	1.54	1.37	1.18	1.33	1.98	0.53	0.60
P ₂ O ₅	0.42	0.57	0.55	0.56	0.39	0.74	0.30	0.27
LOI	2.37	2.83	2.24	2.33	1.76	1.91	2.29	1.71
Total	100.08	100.30	100.37	100.10	100.21	100.29	100.03	100.19
Mg-no.	37.9	34.1	35.4	35.3	35.8	20.1	41.5	43.4
<i>ppm</i>								
Li	26	35	25	24	22	16	46	33
Be	1.0	1.3	1.4	1.4	1.3	2.4	1.1	1.0
Sc	33	30	30	30	39	24	44	42
V	458	342	347	341	469	18	443	420
Cr	8	101	90	82	81	76	74	48
Co	35	31	34	34	43	18	48	51
Ni	9	74	65	59	52	40	40	34
Ga	16.6	18.7	19.2	17.2	20.7	23.3	23.0	21.8
Rb	63.9	54.2	47.1	34.9	60.4	60.5	18.0	19.9
Sr	334	353	343	279	554	341	221	237
Y	36.3	46.6	47.5	45.8	42.8	83.8	39.4	37.1
Zr	197	262	265	265	217	448	185	168
Nb	19.1	26.1	26.1	25.3	21.7	47.7	16.7	15.5
Cs	2.2	2.0	1.9	1.4	2.5	1.2	0.3	1.8
Ba	267	347	269	351	255	328	92	135
La	19.0	25.5	25.9	25.2	19.5	43.1	16.3	15.2
Ce	43.3	57.2	58.7	57.4	45.5	104.2	38.6	35.9
Pr	5.58	7.40	7.52	7.39	5.99	13.24	5.20	4.83
Nd	25.1	33.0	33.6	33.0	27.4	58.9	24.1	22.2
Sm	6.21	8.05	8.09	8.04	6.89	14.60	6.24	5.85
Eu	1.93	2.42	2.56	2.46	2.26	4.39	2.09	2.03
Gd	6.36	8.41	8.24	8.38	7.41	14.77	6.86	6.33
Tb	1.05	1.38	1.39	1.39	1.28	2.50	1.20	1.11
Dy	6.06	7.82	7.90	7.87	7.40	14.56	6.99	6.58
Ho	1.24	1.58	1.60	1.57	1.52	2.94	1.42	1.33
Er	3.09	3.90	3.97	3.94	3.74	7.42	3.56	3.33
Tm	0.45	0.58	0.59	0.59	0.56	1.12	0.54	0.50

(continued)

Table 3: Continued

Location:	N39°03'14", E121°32'46"				N39°01'56", E121°30'27"		N39°04'07", E121°35'58"		N39°00'38", E121°39'07"	
Group:	1	1	1	1	1	1	1		1	
Sample:	03JH001	03JH002	03JH003	03JH004	03JH006	03JH007	03JH008		03JH009	
Yb	2.94	3.75	3.85	3.81	3.69	7.40	3.48		3.27	
Lu	0.48	0.59	0.61	0.61	0.60	1.20	0.56		0.55	
Hf	4.3	5.8	5.8	5.9	5.1	10	4.7		4.3	
Ta	1.0	1.4	1.4	1.4	1.2	2.5	1.0		0.9	
Pb	6.8	4.9	4.7	5.4	4.2	8.1	3.0		3.5	
Th	3.5	4.6	4.6	4.8	2.9	6.6	2.5		2.2	
U	0.7	1.0	1.0	1.0	0.7	1.6	0.6		0.5	
Location:	N39°04'59", E121°47'47"		N39°03'17", E121°55'24"		N39°02'28", E121°53'51"		N39°04'59", E121°47'47"		N38°45'42", E121°07'42"	
Group:	1	1	1	1	2	2	2	2	3	3
Sample:	03JH011	03JH012	03JH016	03JH015	03JH013	03JH024	03JH027	03JH025	03JH026	
<i>wt%</i>										
SiO ₂	47.87	47.45	49.18	47.13	53.08	55.58	55.26	49.58	51.88	
TiO ₂	2.50	2.38	2.24	3.57	0.81	0.66	0.69	1.49	1.31	
Al ₂ O ₃	13.65	13.72	13.52	13.24	13.29	13.70	14.81	14.79	14.95	
TF ₂ O ₃	14.77	14.73	13.44	15.89	7.89	7.90	7.63	9.54	8.38	
MnO	0.22	0.21	0.20	0.21	0.12	0.11	0.11	0.16	0.13	
MgO	6.12	6.40	6.07	6.05	8.94	8.87	7.38	6.47	5.82	
CaO	9.92	10.02	9.62	6.53	7.68	6.07	6.60	7.92	7.60	
Na ₂ O	2.09	2.20	2.38	3.56	2.22	3.18	3.19	2.85	3.48	
K ₂ O	0.93	0.80	1.16	1.08	3.46	1.48	2.14	4.23	4.10	
P ₂ O ₅	0.34	0.31	0.22	0.48	0.22	0.15	0.19	1.34	1.14	
LOI	1.48	1.53	1.92	2.24	2.16	1.94	1.82	1.22	0.82	
Total	99.89	99.75	99.95	99.98	99.85	99.64	99.82	99.59	99.61	
Mg-no.	45.3	46.5	47.5	43.2	69.4	69.2	65.9	57.6	58.1	
<i>ppm</i>										
Li	17	16	24	35	23	17	13	31	24	
Be	0.8	0.7	0.8	1.4	1.1	1.0	1.0	1.2	1.4	
Sc	41	40	51	34	23	27	26	21	19	
V	346	332	414	439	168	164	171	161	142	
Cr	43	43	1	36	795	756	397	152	161	
Co	52	53	47	42	39	36	31	31	25	
Ni	27	27	2	24	238	171	110	74	65	
Ga	20.4	20.1	21.9	22.8	17.7	17.2	18.8	19.9	20.4	
Rb	28.6	22.1	38.7	59.6	49.6	39.5	55.2	120	125	
Sr	316	298	289	257	422	488	767	2405	2341	
Y	35.3	33.6	33.1	35.6	15.8	17.3	17.1	33.4	33.6	
Zr	173	151	138	244	132	103	108	199	302	
Nb	16.5	15.7	12.9	28.4	6.4	5.6	6.0	26.1	30.8	
Cs	0.7	0.5	0.8	0.9	0.4	0.5	0.6	1.4	1.7	

(continued)

Table 3: Continued

Location:	N39°04'59", E121°47'47"		N39°03'17", E121°55'24"		N39°02'28", E121°53'51"		N39°04'59", E121°47'47"		N38°45'42", E121°07'42"		N38°45'22", E121°07'44"					
Group:	1		1		1		2		2		2		3		3	
Sample:	03JH011	03JH012	03JH016		03JH015		03JH013		03JH024		03JH027	03JH025		03JH026		
Ba	320	264	166		595		1137		777		996	5027		4223		
La	18.6	17.4	12.3		27.9		21.1		16.7		21.2	128		144		
Ce	42.1	39.7	30.1		61.4		44.4		31.7		42.8	273		292		
Pr	5.45	5.14	4.14		7.80		5.36		4.05		5.16	30.4		30.7		
Nd	24.2	23.3	19.8		33.9		22.2		16.7		21.1	115		110		
Sm	5.83	5.64	5.23		7.58		4.28		3.41		4.06	16.0		15.0		
Eu	2.09	2.04	1.80		2.52		1.33		1.04		1.28	4.22		3.98		
Gd	6.21	6.00	5.62		7.59		3.95		3.27		3.75	13.8		13.3		
Tb	1.07	1.04	1.01		1.20		0.56		0.51		0.54	1.50		1.43		
Dy	6.19	5.95	5.94		6.65		2.91		2.89		2.98	6.78		6.66		
Ho	1.25	1.18	1.17		1.27		0.54		0.57		0.57	1.05		1.07		
Er	3.17	2.96	2.95		3.12		1.33		1.44		1.44	2.68		2.74		
Tm	0.47	0.44	0.45		0.46		0.19		0.22		0.21	0.32		0.36		
Yb	3.13	2.88	2.94		3.01		1.26		1.46		1.48	2.16		2.32		
Lu	0.51	0.47	0.48		0.48		0.20		0.24		0.24	0.35		0.36		
Hf	4.2	3.7	3.7		5.7		3.3		2.5		2.8	3.5		5.2		
Ta	1.0	0.9	0.8		1.7		0.3		0.3		0.3	0.9		1.2		
Pb	4.0	3.4	1.9		16		11		8.0		14	16		20		
Th	1.9	1.7	1.8		3.7		3.0		3.1		3.0	3.1		4.9		
U	0.4	0.4	0.4		0.8		0.6		0.8		0.8	0.7		1.2		

Group 1 dikes display considerable variations in $(^{87}\text{Sr}/^{86}\text{Sr})_i$ (0.7060–0.7153), $\epsilon_{\text{Nd}}(t)$ values (–0.8 to –6.5), $\epsilon_{\text{Hf}}(t)$ values (–2.5 to –7.8), and $\Delta\epsilon_{\text{Hf}}(t)$ values of –1.1 to –6.4 (Fig. 7 and Table 4). In the $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ vs $(^{87}\text{Sr}/^{86}\text{Sr})_i$ diagrams (Fig. 7a and b), Group 1 dikes define a linear trend, indicating a two-component mixing process. They have negative $\Delta\epsilon_{\text{Hf}}(t)$ values (–6.4 to –1.1) [where $\Delta\epsilon_{\text{Hf}}(t) = 1.33\epsilon_{\text{Nd}}(t) + 3.19 - \epsilon_{\text{Hf}}(t)$] and plot close to or below the mantle array [$\epsilon_{\text{Hf}}(t) = 1.33\epsilon_{\text{Nd}}(t) + 3.19$] of Vervoort *et al.* (1999) in the $\epsilon_{\text{Hf}}(t)$ and $\Delta\epsilon_{\text{Hf}}(t)$ vs $\epsilon_{\text{Nd}}(t)$ diagrams (Fig. 7c and d).

Group 2

Group 2 dikes also plot in the subalkaline field (Fig. 3a) and are characterized by high MgO (7.38–8.94 wt%), Cr (397–795 ppm) and Ni (110–238 ppm), low TiO₂ (0.66–0.81 wt%) and total Fe₂O₃ (7.6–7.9 wt%) concentrations at intermediate silica contents (SiO₂ 53.1–55.6 wt%; Table 3, Figs 3 and 4), similar to the geochemical characteristics of high-Mg andesites (Tatsumi, 1982, 2006; Tatsumi & Maruyama, 1989; Shinjo, 1999; Yögodzinski *et al.*, 2001;

Wang *et al.*, 2002; Zhang *et al.*, 2003). They are medium-K to high-K calc-alkaline (Fig. 3c). Group 2 intermediate dikes are enriched in LREE and are relatively depleted in HREE with $(\text{La}/\text{Yb})_{\text{CN}}$ values of 8.2–12.0 and $(\text{Dy}/\text{Yb})_{\text{CN}}$ values of 1.2–1.4 with no negative Eu anomalies in the chondrite-normalized REE patterns (Fig. 5b). In the PM-normalized trace element diagram (Fig. 6b), Group 2 dikes are enriched in LILE (including Rb, Ba, Th and U) and LREE with positive Ba and Sr anomalies, and are depleted in HFSE with strong negative Nb, Ta and Ti anomalies. Group 2 dikes have relatively low $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios (0.7063–0.7072) compared with Group 1 and variable $\epsilon_{\text{Nd}}(t)$ values of –3.0 to –9.5, $\epsilon_{\text{Hf}}(t)$ values of –3.2 to –10.1 and $\Delta\epsilon_{\text{Hf}}(t)$ values of –3.9 to +3.5 (Fig. 7 and Table 4).

Group 3

Two dikes sampled from the Liaodong Peninsula are identified as Group 3. They are alkaline (Fig. 3a) with K₂O/Na₂O ratios of 1.2–1.5 and total alkali (K₂O + Na₂O) contents of 7.1–7.6 wt%; they are thus shoshonitic (Fig. 3c).

Table 4: Sr, Nd and Hf isotopic compositions of mafic dikes from the Liaodong Peninsula of northeastern North China Craton

Sample	Group	Rb (ppm)	Sr (ppm)	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr	2σ	(⁸⁷ Sr/ ⁸⁶ Sr) _i *	Sm (ppm)	Nd (ppm)	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd	2σ	ε _{Nd} (t)*	T _{DM} * (Ma)	f _{Sm/Nd}	¹⁷⁶ Lu/ ¹⁷⁷ Hf	¹⁷⁶ Hf/ ¹⁷⁷ Hf	2σ	ε _{Hf} (t)*	Δε _{Hf} (t)	T _{DM} * (Ma)	f _{Lu/Hf}
03JH001	1	63.4	342	0.5374	0.714373	14	0.71275	6.47	26.1	0.1497	0.512370	9	-3.9	1851	-0.2	0.01570	0.282547	4	-5.5	-3.5	1633	-0.5
03JH002	1	53.0	364	0.4221	0.713472	13	0.71219	8.66	35.6	0.1472	0.512345	8	-4.4	1840	-0.3	0.01459	0.282540	4	-5.6	-3.0	1574	-0.6
03JH003	1	44.9	340	0.3820	0.712448	10	0.71129	8.72	35.8	0.1473	0.512355	14	-4.2	1820	-0.3	—	—	—	—	—	—	—
03JH004	1	33.1	279	0.3434	0.711094	12	0.71005	8.66	35.6	0.1473	0.512376	14	-3.8	1772	-0.3	0.01467	0.282548	4	-5.4	-3.5	1562	-0.6
03JH006	1	54.2	507	0.3095	0.710026	13	0.70909	7.22	28.3	0.1542	0.512447	13	-2.6	1796	-0.2	0.01647	0.282593	6	-4.0	-3.8	1581	-0.5
03JH007	1	58.9	347	0.4915	0.711197	12	0.70971	15.1	61.6	0.1484	0.512405	10	-3.2	1734	-0.2	—	—	—	—	—	—	—
03JH008	1	15.0	211	0.2051	0.707055	13	0.70643	6.17	23.7	0.1576	0.512493	11	-1.8	1779	-0.2	0.01699	0.282551	5	-5.5	-6.4	1963	-0.5
03JH009	1	17.2	217	0.2287	0.706692	12	0.70600	5.99	22.7	0.1595	0.512536	14	-1.0	1722	-0.2	0.01801	0.282584	4	-4.5	-6.4	1976	-0.5
03JH011	1	24.2	295	0.2368	0.708505	11	0.70779	5.81	24.1	0.1460	0.512396	11	-3.3	1693	-0.3	0.01732	0.282634	9	-2.7	-1.4	1542	-0.5
03JH012	1	18.4	275	0.1939	0.707707	14	0.70712	5.64	23.2	0.1472	0.512389	13	-3.5	1739	-0.3	0.01792	0.282640	10	-2.5	-1.1	1572	-0.5
03JH016	1	32.5	257	0.3664	0.707561	13	0.70645	5.18	19.3	0.1622	0.512547	13	-0.8	1780	-0.2	0.01822	0.282603	5	-3.9	-6.0	1947	-0.5
03JH015	1	51.8	252	0.5958	0.717103	13	0.71530	7.72	34.7	0.1345	0.512221	11	-6.5	1785	-0.3	0.01186	0.282467	19	-7.8	-2.4	1557	-0.6
03JH013	2	41.7	391	0.3087	0.708164	14	0.70723	4.11	21.0	0.1184	0.512376	11	-3.0	1237	-0.4	0.00861	0.282586	16	-3.2	-2.4	1181	-0.7
03JH024	2	32.9	433	0.2198	0.707462	15	0.70680	3.24	15.9	0.1237	0.512173	12	-7.1	1651	-0.4	0.01360	0.282409	4	-10.1	-3.9	1786	-0.6
03JH027	2	45.7	681	0.1942	0.706879	13	0.70629	3.72	19.6	0.1151	0.512038	13	-9.5	1716	-0.4	0.01244	0.282522	15	-6.0	+3.5	1481	-0.6
03JH025	3	95.6	2219	0.1247	0.706625	14	0.70625	16.2	115	0.0847	0.511796	12	-13.4	1597	-0.6	0.01390	0.282386	6	-11.0	+3.6	1856	-0.6
03JH026	3	103	2190	0.1357	0.706544	11	0.70613	15.0	108	0.0840	0.511804	11	-13.2	1579	-0.6	0.00974	0.282355	4	-11.5	+2.9	1647	-0.7

*The ¹⁴⁷Sm/¹⁴⁴Nd and ¹⁴³Nd/¹⁴⁴Nd ratios at the present time are 0.1967 and 0.512638 for chondrite, and 0.222 and 0.51315 for depleted mantle, respectively. $\lambda = 6.54 \times 10^{-12} \text{ a}^{-1}$. The ¹⁷⁶Hf/¹⁷⁷Hf and ¹⁷⁶Lu/¹⁷⁷Hf ratios at the present time are 0.282772 and 0.0332 for chondrite, and 0.28325 and 0.0384 for depleted mantle, respectively (Blichert-Toft & Albarède, 1997; Griffin *et al.*, 2000). $\lambda = 1.867 \times 10^{-11} \text{ a}^{-1}$ (Soderlund *et al.* 2004). t is the crystallization age of zircon.

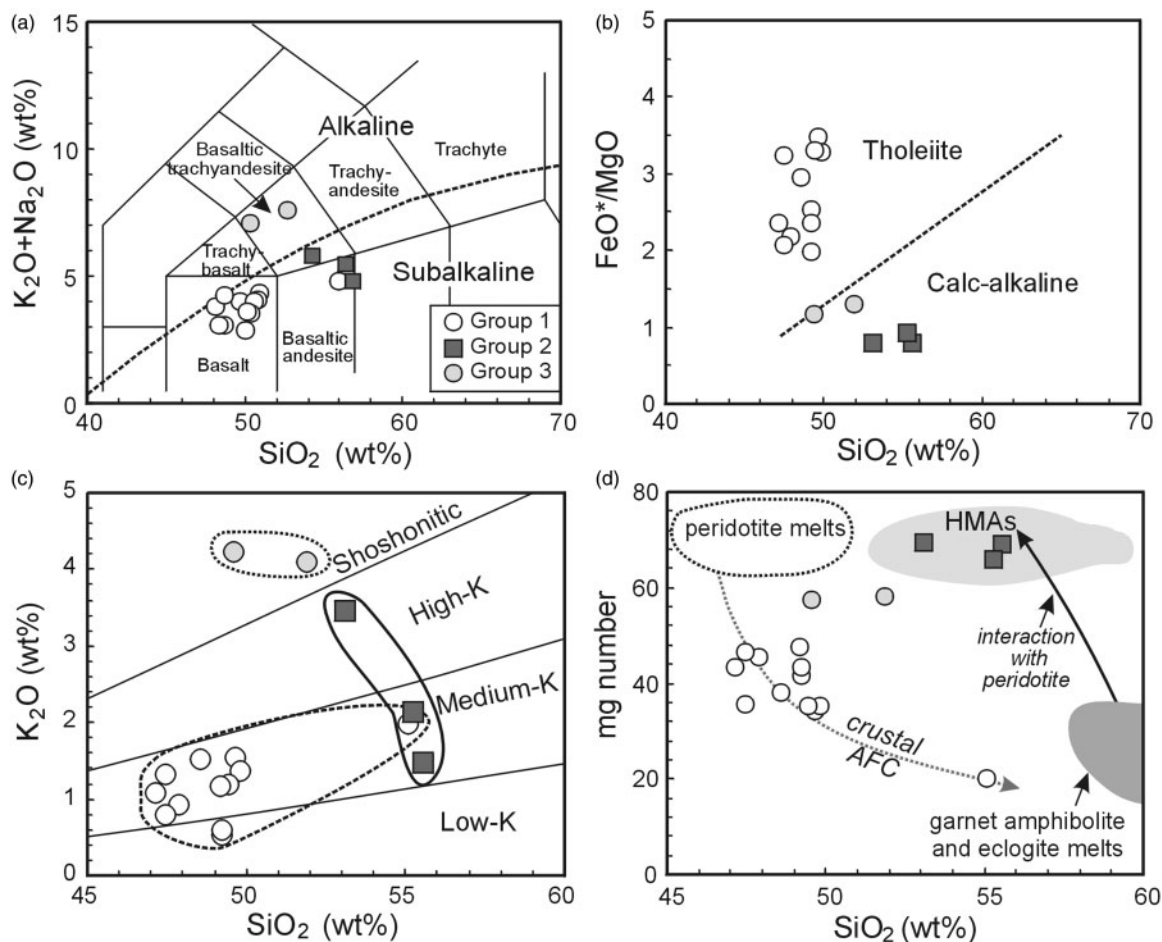


Fig. 3. Plots of (a) total alkalis (Le Maitre, 2002), (b) FeO^*/MgO , (c) K_2O (Ringwood, 1989), and (d) mg-number vs SiO_2 for Late Triassic dikes from the Liaodong Peninsula, northeastern North China Craton. The fields of high-Mg andesites (HMAs), mantle peridotite melts and garnet amphibolite and eclogite melts in (d) are from Kelemen (1995), Stern & Kilian (1996) and Rapp *et al.* (1999). Crustal AFC was calculated following DePaolo (1981) with a relatively hot mantle wedge, and 20% clinopyroxene as a fractionating phase.

They have mafic to intermediate compositions (SiO_2 49.6–51.9 wt%, MgO 5.8–6.5 wt%), and Cr and Ni contents between those of Groups 1 and 2 (Table 3 and Fig. 3b). They are highly enriched in LREE with $(\text{La}/\text{Yb})_{\text{CN}}$ values of 42.7–44.6 and $(\text{Dy}/\text{Yb})_{\text{CN}}$ values of 1.9–2.0, distinct from Groups 1 and 2, and are without negative Eu anomalies (Fig. 5b). In the PM-normalized trace element diagram (Fig. 6b), Group 3 rocks are enriched in LILE with positive K, Ba and Sr anomalies, and are depleted in HFSE with pronounced negative Nb, Ta, Zr, Hf and Ti anomalies. Nb–Ta fractionation is evident in the PM-normalized trace element patterns, with Nb/Ta ratios of 26.7–29.3 (Fig. 6b). The mafic dikes of Group 3 have relatively low $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios (0.7061–0.7062) and strongly negative $\epsilon_{\text{Nd}}(t)$ (–13.2 to –13.4) and $\epsilon_{\text{Hf}}(t)$ values (–11.0 to –11.5). They have positive $\Delta\epsilon_{\text{Hf}}(t)$ values of +2.9 to +3.6 (Fig. 7 and Table 4), distinct from Group 1 dikes.

DISCUSSION

The major and trace element characteristics and Sr–Nd–Hf isotope compositions of the primitive and evolved magmatic rocks in the Liaodong Peninsula can provide constraints on the nature of the mantle source, the processes of partial melting, crustal-level evolution and geodynamic setting. Moreover, there may be a relationship between the petrogenesis of the post-collisional mafic dikes and the evolution of the Sulu orogenic belt.

Magma sources and petrogenesis

Group 1

The Group 1 rocks have variable SiO_2 (47.2–55.1 wt%), MgO (2.0–6.4 wt%), Cr (1.1–101 ppm), Ni (1.5–74 ppm), $(^{87}\text{Sr}/^{86}\text{Sr})_i$ (0.7060–0.7153), $\epsilon_{\text{Nd}}(t)$ (–0.8 to –6.5) and $\epsilon_{\text{Hf}}(t)$ (–2.5 to –7.8) values. All these features indicate that none of these dike samples represent primary magma

Table 5: Two-component mixing, AFC and EC-AFC parameters

	Sr	Nd
<i>Compositional parameters</i>		
Magma initial concentration (ppm), C_m^0	200	10
Magma isotope ratio	0.7038	0.51252
Magma trace element distribution coefficient, D_m	1.5	0.25
Assimilant initial concentration (ppm), C_a^0	350	60
Assimilant isotope ratio	0.7250	0.51185
Assimilant trace element distribution coefficient, D_a	1.5	0.25
<i>Thermal parameters</i>		
Magma liquidus temperature, $T_{l,m}$	1280°C	
Magma initial temperature, T_m^0	1280°C	
Assimilant liquidus temperature, $T_{a,m}$	1000°C	
Assimilant initial temperature, T_a^0	300°C	
Solidus temperature, T_s	900°C	
Equilibration temperature, T_{eq}	980°C	
Crystallization enthalpy, Δh_{cry} (J/kg)	396000	
Isobaric specific heat of magma, $C_{p,m}$ (J/kg per K)	1484	
Fusion enthalpy, Δh_{fus} (J/kg)	270000	
Isobaric specific heat of assimilant, $C_{p,a}$ (J/kg per K)	1370	

compositions. In the $\epsilon_{Nd}(t)$ and $\epsilon_{Hf}(t)$ vs $(^{87}Sr/^{86}Sr)_i$ diagrams (Fig. 7a and b), the Group 1 dikes define a mixing line between two components; that is, a component (mafic magma) with low $(^{87}Sr/^{86}Sr)_i$ (<0.7060) and high $\epsilon_{Nd}(t)$ (>0) and $\epsilon_{Hf}(t)$ (>-1.3) values, and another component (crustal material) with high $(^{87}Sr/^{86}Sr)_i$ (>0.7153) and negative $\epsilon_{Nd}(t)$ (<-6.5) and $\epsilon_{Hf}(t)$ (<-7.8) values. Furthermore, the positive correlations between CaO, Al_2O_3 (and Ca/Al ratios, not shown) and MgO (Fig. 4) are consistent with extensive clinopyroxene and feldspar fractionation. Plagioclase fractionation is also indicated by the negative Sr and Ba anomalies in the PM-normalized trace element patterns (Fig. 6b). The increase in total Fe_2O_3 and TiO_2 concentrations with decreasing MgO abundances (Fig. 4) may be the result of accumulation of Fe–Ti oxides. All these characteristics preclude a simple, common evolution by closed-system fractionation processes; instead, they suggest the operation of combined processes of crustal assimilation and fractional crystallization (AFC) in the petrogenesis of the magma.

The energy-constrained assimilation and fractional crystallization (EC-AFC) model (Bohrson & Spera, 2001; Spera & Bohrson, 2001) provides a rigorous approach to the simulation of AFC processes. First, we selected reasonable ranges of the initial parameters required in the EC-AFC model based on the isotopic and geochemical

characteristics of the magmas in the Liaodong Peninsula. The likely crustal materials involved in the petrogenesis of Group 1 dikes have high $(^{87}Sr/^{86}Sr)_i$ ratios, similar to those of upper crustal materials and crustal-derived granites in the Liaodong Peninsula and NCC as a whole (Jahn *et al.*, 1999; Yang *et al.*, 2006a). Therefore, an upper crustal composition was selected with a Sr content of 350 ppm, Nd concentration of 26 ppm, $(^{87}Sr/^{86}Sr)_i$ of 0.7250 and $\epsilon_{Nd}(t)$ value of -10 [$(^{143}Nd/^{144}Nd)_i = 0.51185$]. As the parental magma of Group 1 dikes had $(^{87}Sr/^{86}Sr)_i < 0.706$ and $\epsilon_{Nd}(t) > 0$, we selected values of 0.7038 for Sr and $\epsilon_{Nd}(t) = +3.0$ for the Nd isotopic compositions of the parental magma. The Sr and Nd contents of Group 1 dikes range from 221 to 554 ppm and 20 to 34 ppm, respectively (Table 3). In the $(^{87}Sr/^{86}Sr)_i$ vs Sr diagram (Fig. 8b), the Group 1 dikes define a rough line back to a $(^{87}Sr/^{86}Sr)_i$ of 0.7038 and Sr contents of 160–180 ppm in the parental magma. However, fractionation of clinopyroxene and plagioclase will decrease the Sr content of magmas, whereas crustal assimilation will increase the Nd concentration. Thus, we selected Sr and Nd abundances for the parental magma of 200 ppm and 10 ppm, respectively. The physical characteristics of the magma body–country rock system are similar to those suggested by Bohrson & Spera (2001) and are listed in Table 5. Using the selected values of these initial parameters, we performed calculations using the EC-AFC (<http://magma.geol.ucsb.edu>) calculation programs. In addition, AFC calculations (DePaolo, 1981) were also performed. The output from our EC-AFC and AFC simulations provides model curves to fit the correlation trends between $(^{87}Sr/^{86}Sr)_i$ and Sr, and $\epsilon_{Nd}(t)$ and $(^{87}Sr/^{86}Sr)_i$ (Fig. 8). These parameters provide important constraints on the characteristics of the primitive magma, the nature of the crustal contaminant and AFC processes involved in the petrogenesis of the Group 1 dikes.

Although none of these dike samples represent primary melts, the samples with high MgO contents (≥ 6.0 wt%) are tholeiitic and have low SiO_2 abundances (47.1–49.2 wt%), relatively low $(^{87}Sr/^{86}Sr)_i$ (down to 0.7060) and relatively high $\epsilon_{Nd}(t)$ (up to -0.8) and $\epsilon_{Hf}(t)$ (up to -2.5) values, indicating that the parental magmas to Group 1 dikes have $(^{87}Sr/^{86}Sr)_i < 0.7060$, $\epsilon_{Nd}(t) > 0$ and $\epsilon_{Hf}(t) > -2.5$. The high-MgO samples (MgO ≥ 6.0 wt%) have relatively high Nb, Ta, and $(Nb/Th)_N$ up to 1.1 (Fig. 9a) with no negative Nb and Ta anomalies in the PM-normalized trace element patterns (Fig. 6a), indicating that the parental magma to Group 1 mafic dikes was enriched in HFSE and LREE relative to LILE. The high-MgO samples also have high total Fe_2O_3 , TiO_2 , Al_2O_3 and CaO contents (Table 3), between the major element compositions of glasses produced by partial melting experiments on natural anhydrous fertile spinel peridotite at conditions ranging from 0.2 to 3.0 GPa and 1100 to 1375°C at melt fractionation of $<30\%$ (HK-66; Hirose & Kushiro,

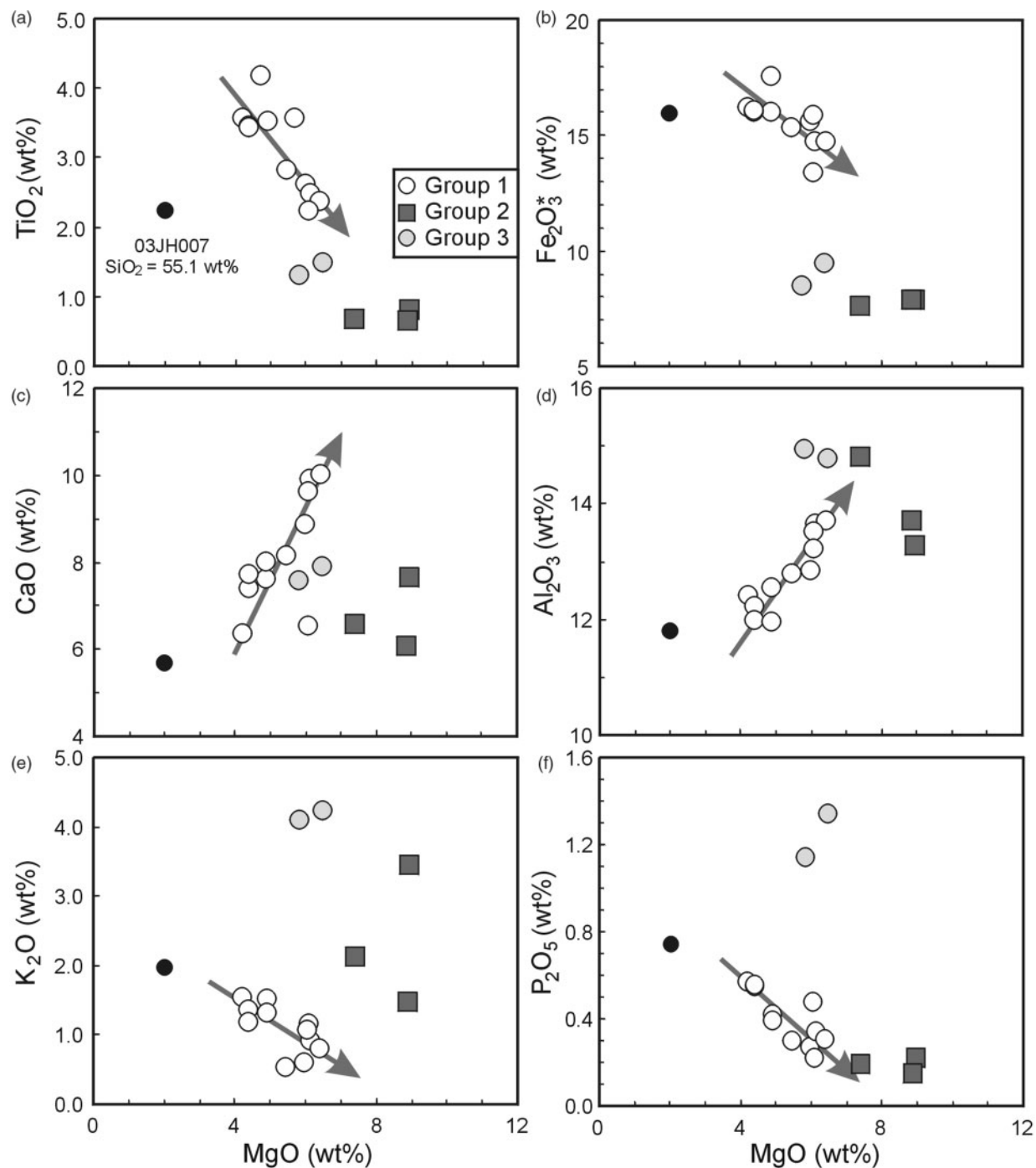


Fig. 4. Various oxide plots against MgO for mafic dikes from the Liaodong Peninsula, northeastern North China Craton: (a) TiO_2 ; (b) Fe_2O_3^* ; (c) CaO; (d) Al_2O_3 ; (e) K_2O ; (f) P_2O_5 .

1993) and on a fertile peridotite at conditions ranging from 2 to 30 kbar (Falloon *et al.*, 1988) (Fig. 9b). Therefore, the parental magmas of Group 1 dikes should have low SiO_2 abundances and high total Fe_2O_3 , TiO_2 , Al_2O_3 and CaO contents, with no negative Nb, Ta and Ti anomalies,

similar to experimental melts derived from partial melting of fertile peridotites (Falloon *et al.*, 1988; Hirose & Kushiro, 1993).

The variable major and trace element abundances and Sr and Nd isotopic compositions of the Group 1 dikes

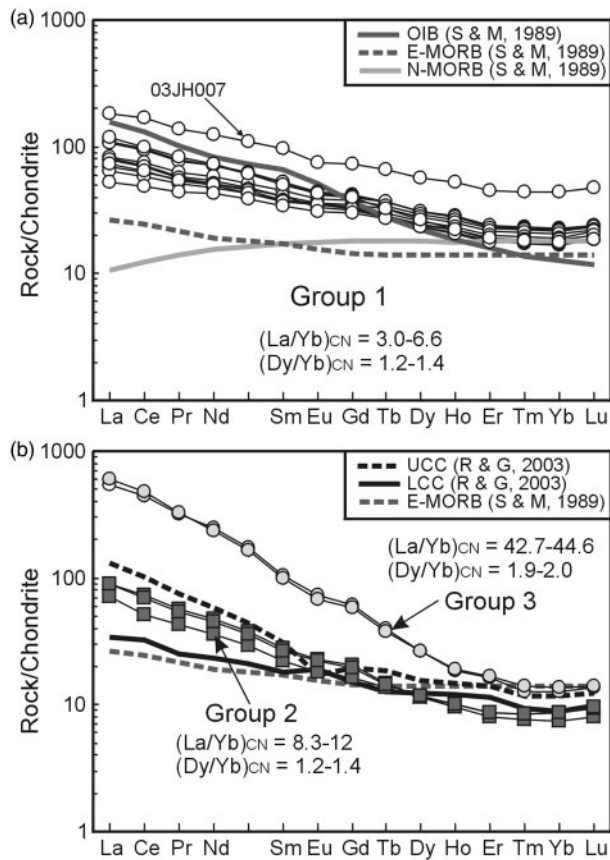


Fig. 5. Chondrite-normalized REE patterns for mafic dikes from the Liaodong Peninsula; (a) Group 1; (b) Groups 2 and 3. The chondrite normalizing values are from Sun & McDonough (1989). The data for oceanic island basalt (OIB), normal mid-ocean ridge basalt (N-MORB) and enriched mid-ocean ridge basalt (E-MORB) are from Sun & McDonough (1989); upper and lower continental crust (UCC and LCC) values are from Rudnick & Gao (2003).

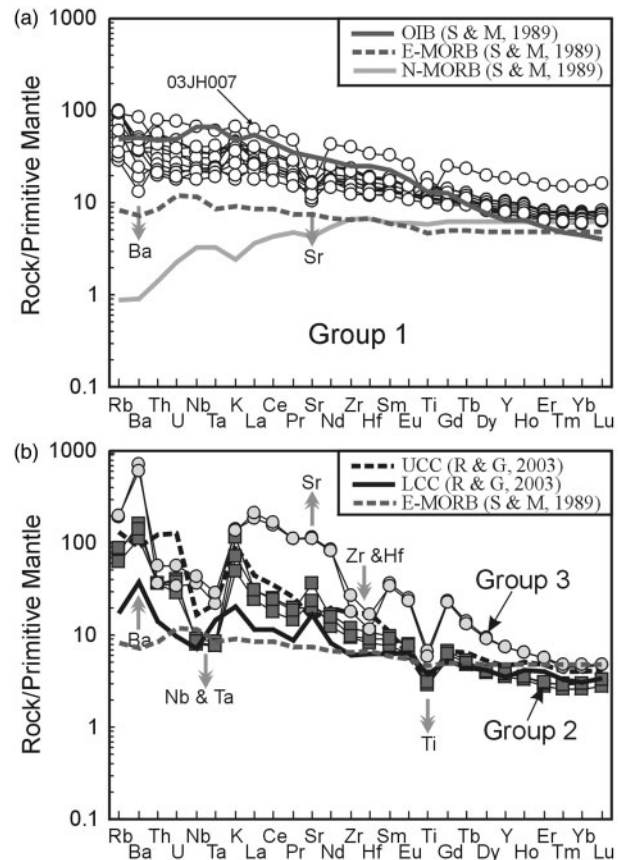


Fig. 6. Primitive mantle (PM) normalized trace element diagrams for (a) Group 1 and (b) Groups 2 and 3 from the Liaodong Peninsula. The elements are arranged in order of decreasing incompatibility from left to right (from Sun & McDonough, 1989). The data for oceanic island basalt (OIB), normal mid-ocean ridge basalt (N-MORB) and enriched mid-ocean ridge basalt (E-MORB) are from Sun & McDonough (1989); upper and lower continental crust (UCC and LCC) values are from Rudnick & Gao (2003).

strongly suggest the involvement of a crustal component in their petrogenesis. The positive correlation between $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and $(\text{La}/\text{Yb})_{\text{CN}}$ ratios and negative correlation between $\epsilon_{\text{Nd}}(t)$ values and $(\text{La}/\text{Yb})_{\text{CN}}$ ratios (Fig. 9c and d) indicate that the variable major and trace element characteristics were not produced by simple differentiation of a mafic magma, but resulted from assimilation of a crustal component with low MgO , $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ values and high LREE abundance and $(^{87}\text{Sr}/^{86}\text{Sr})_i$ compared with the products of fractional crystallization. The Group 1 dikes have variable Ce/Pb ratios (3.8–15.7) intermediate between those of oceanic basalts (~ 25 , Sun & McDonough, 1989) and the upper continental crust (~ 3.7 , Rudnick & Gao, 2003). In addition, Ce/Pb ratios decrease and Zr/Sm ratios (not shown) increase with increasing $(^{87}\text{Sr}/^{86}\text{Sr})_i$, suggesting that upper continental crustal material was involved in their petrogenesis. This is also evidenced by the elevated Rb/Sr , Th , U and La contents

with decreasing MgO concentration (Table 2) and the presence of inherited zircons with ages of 1.1–0.8 Ga in the Group 1 dikes (Fig. 2b) (Yang *et al.*, 2004a). In addition, the crustal component ought to have relatively high $(^{87}\text{Sr}/^{86}\text{Sr})_i$ (>0.715) and moderately negative $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ values, distinct from those of Late Triassic granites with $(^{87}\text{Sr}/^{86}\text{Sr})_i < 0.710$, $\epsilon_{\text{Nd}}(t)$ values of -14 to -16 and $\epsilon_{\text{Hf}}(t)$ values of -13 (Fig. 7) that were derived from partial melting of lower crustal materials (Yang *et al.*, 2007a). All these factors suggest an involvement of upper crustal materials in the origin of Group 1 dikes.

In general, low La/Yb ratios reflect a melting regime dominated by relatively large melt fractions and/or spinel as the predominant residual phase, whereas high La/Yb ratios are indicative of smaller melt fractions and/or garnet control. Sample 03JH007, having relatively lower MgO and higher SiO_2 and trace element concentrations

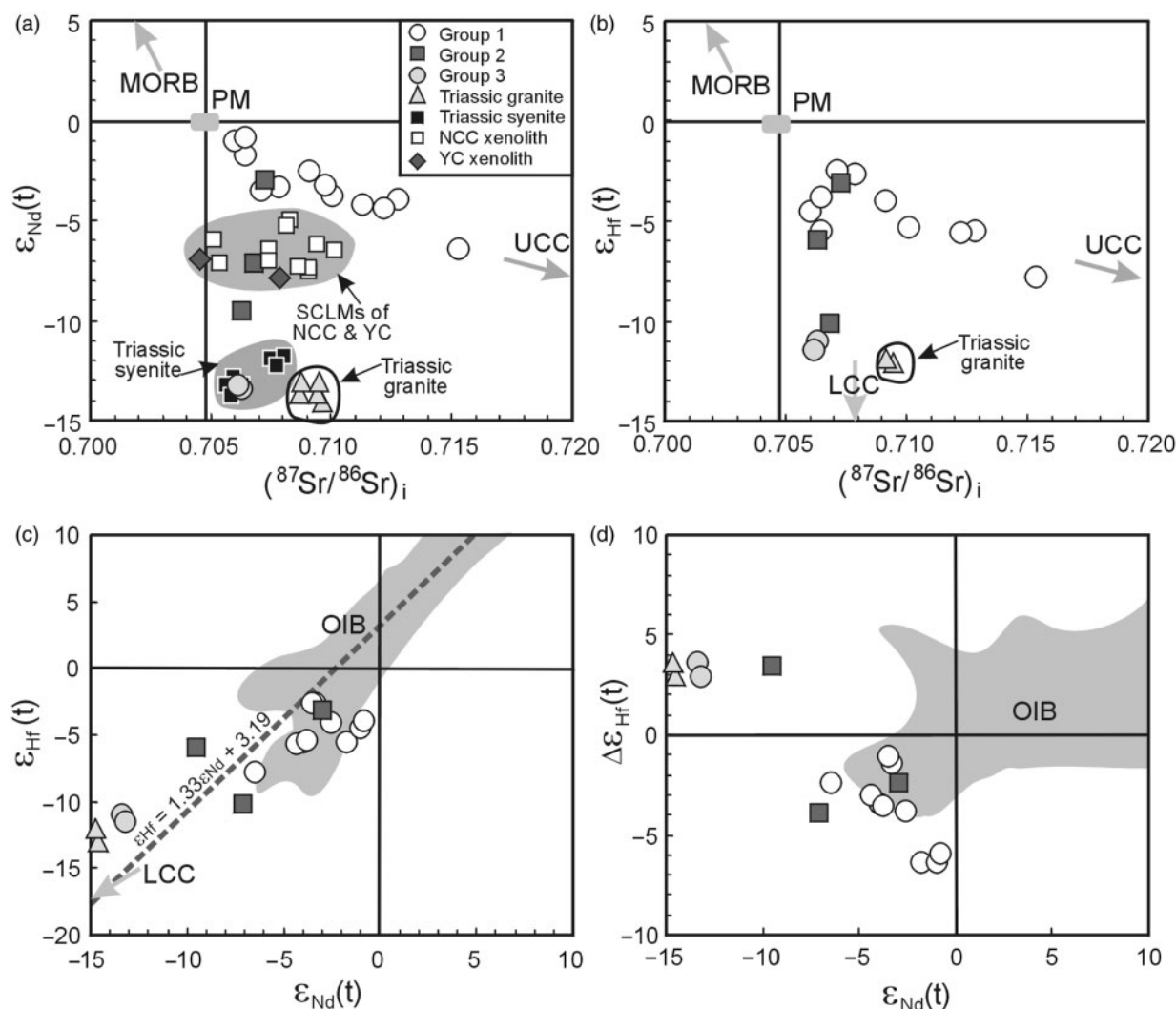


Fig. 7. (a) $\epsilon_{\text{Nd}}(t)$ and (b) $\epsilon_{\text{Hf}}(t)$ vs $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and (c) $\epsilon_{\text{Hf}}(t)$ and (d) $\Delta\epsilon_{\text{Hf}}(t)$ vs $\epsilon_{\text{Nd}}(t)$ plots for mafic dikes from the Liaodong Peninsula. $\Delta\epsilon_{\text{Hf}}(t)$ is defined as $\epsilon_{\text{Hf}}(t) = [1.33\epsilon_{\text{Nd}}(t) + 3.19]$ such that a sample with positive $\Delta\epsilon_{\text{Hf}}(t)$ lies above and a sample with negative $\Delta\epsilon_{\text{Hf}}(t)$ lies below the mantle array of Vervoort *et al.* (1999). The Sr–Nd data for mantle xenoliths from the subcontinental lithospheric mantle (SCLM) in the North China and Yangtze cratons are from Wu *et al.* (2006a) and Zhang *et al.* (2001), respectively. The Sr–Nd–Hf isotope data for Triassic syenites and monzogranites in the Liaodong Peninsula and the Nd–Hf isotope data for lower crustal-derived xenoliths in the eastern NCC are from Zheng *et al.* (2004) and Yang *et al.* (2007a, and unpublished data), respectively. The upper and lower continental crust are after Jahn *et al.* (1999), Zheng *et al.* (2004) and Yang *et al.* (2006a). The field for OIB is based on the data of Vervoort *et al.* (1999).

than other samples of Group 1, may have formed by relatively low degrees of partial melting. In the La_{CN} vs MgO (not shown), $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and $\epsilon_{\text{Nd}}(t)$ vs $(\text{La}/\text{Yb})_{\text{CN}}$ diagrams (Fig. 9c and d), the trends defined by the Group 1 dikes show that the high-MgO samples have low La/Yb ratios and $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios and high $\epsilon_{\text{Nd}}(t)$ values, indicating that the primary magma parental to Group 1 dikes would have had low La/Yb and $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios and high $\epsilon_{\text{Nd}}(t)$ values. Based on geochemical modeling, a 1–15% partial melt of spinel peridotite ought to have relatively low La/Yb and Dy/Yb . In the Dy/Yb vs La/Yb diagram, (Fig. 10) the Group 1 dikes define a trend, showing that

the high-MgO samples have low La/Yb and Dy/Yb . Therefore, the relatively low $(\text{La}/\text{Yb})_{\text{CN}}$ (3.0–6.6) and $(\text{Dy}/\text{Yb})_{\text{CN}}$ (1.2–1.4) (Table 2), in combination with relatively flat MREE to HREE patterns (Fig. 5a) for the high-MgO samples of the Group 1 dikes, suggest that they may have formed by relatively high degree melting of a mantle source in the spinel stability field.

The geochemical and isotopic data indicate that the Group 1 dikes were the result of upper crustal assimilation and crystal fractionation of mafic magmas derived from high percentage partial melting of a fertile mantle in the spinel stability field. The Group 1 dikes have negative

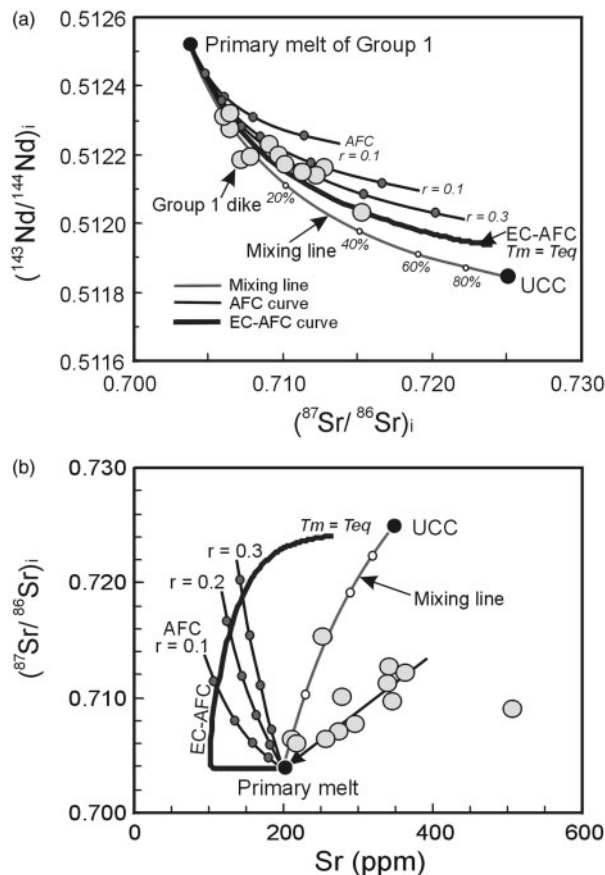


Fig. 8. (a) $(^{143}\text{Nd}/^{144}\text{Nd})_i$ vs $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and (b) $(^{87}\text{Sr}/^{86}\text{Sr})_i$ vs Sr (ppm) plots showing two-component mixing, AFC and EC-AFC calculations. The parameters are listed in Table 5. For two-component mixing trends, symbols represent a mixed component of 20%. For AFC trends with $r = 0.1, 0.2$ and 0.3 , symbols represent fraction of melt (F) increments of 0.2 but are terminated at $F = 0.1$. The UCC data are from Jahn *et al.* (1999) and Yang *et al.* (2006a) with 350 ppm Sr, 60 ppm Nd, $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.7250$ and $\epsilon_{\text{Nd}}(t) = -10$ [$(^{143}\text{Nd}/^{144}\text{Nd})_i = 0.51185$].

$\Delta\epsilon_{\text{Hf}}$ signatures, indicating that melts in equilibrium with garnet-bearing residua exhibit greater Lu/Hf fractionation than Sm/Nd, such that with time the crystallization products of these melts will evolve, over time periods in excess of 1 Gyr, to isotopic compositions below the Nd–Hf isotope array with negative $\Delta\epsilon_{\text{Hf}}$ (Fig. 7c and d). As summarized by Davies *et al.* (2006), two mantle source components have been proposed to explain the origin of negative $\Delta\epsilon_{\text{Hf}}$ signatures: sub-cratonic lithospheric mantle and recycled subducted oceanic crust (Salters & White, 1998; Griffin *et al.*, 2000; Janney *et al.*, 2002; Nowell *et al.*, 2004). However, mineral assemblages, and geochemical and isotopic compositions of mantle xenoliths in Paleozoic kimberlites show that the lithospheric mantle beneath both the North China and Yangtze cratons was relatively ancient, refractory mantle (Menzies *et al.*, 1993; Griffin *et al.*, 1998; Xu *et al.*, 2001; Zhang *et al.*, 2001, 2004).

The lithospheric mantle has negative Nb and Ta anomalies in PM-normalized trace element diagrams (Wu *et al.*, 2006a) and has enriched Sr and Nd isotopic compositions with $^{87}\text{Sr}/^{86}\text{Sr}_{(213\text{ Ma})}$ of 0.7045–0.7094 and $\epsilon_{\text{Nd}}(213\text{ Ma})$ values of -4.3 to -8.0 (Fig. 7a; Zhang *et al.*, 2001; Wu *et al.*, 2006a). These characteristics are distinct from those of the parental magmas of the Group 1 dikes, precluding an ancient lithospheric mantle source for the Group 1 dikes. Thus, we propose that the parental magmas of Group 1 dikes were derived from partial melting of a relatively fertile, sub-lithospheric (asthenospheric) mantle source beneath the continental lithospheric mantle in the Liaodong Peninsula.

Group 2

The Group 2 dikes have variable Sr, Nd and Hf isotopic compositions (Fig. 7). In the $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ vs $(^{87}\text{Sr}/^{86}\text{Sr})_i$ diagrams (Fig. 7a and b), the trends of Group 2 dikes suggest mixing between a component with high $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ values and low $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios, and one with low $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ values and low $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios. They have intermediate silica contents (SiO_2 53.1–55.6 wt%), but with high MgO (7.4–8.9 wt%, mg-number = 65.9–69.4), Cr (397–795 ppm) and Ni (110–238 ppm) abundances (Table 2; Fig. 3d), similar to the geochemical characteristics of high-Mg andesites (Tatsumi & Maruyama, 1989; Shinjo, 1999; Yögodzinski *et al.*, 2001; Wang *et al.*, 2002; Zhang *et al.*, 2003).

Three processes can generate a primitive high-Mg andesite: (1) partial melting of a hydrous mantle source (e.g. Kushiro, 1974; Tatsumi, 1982, 2006; Hirose, 1997); (2) interaction of melts formed by slab melting with a mantle wedge component (e.g. Yögodzinski *et al.*, 1994; Kelemen, 1995; Stern & Kilian, 1996; Rapp *et al.*, 1999); (3) melting of foundered lower crust, followed by interaction with mantle peridotite (Kay & Kay, 1993; Xu *et al.*, 2002). However, partial melts from a hydrous mantle source at high temperature ($>900^\circ\text{C}$) should be in isotopic equilibrium with their source, and thus would have homogeneous isotopic compositions, which is not consistent with the observations in this study (Fig. 7). Crustal assimilation by mantle-derived melts would reduce their MgO, Cr and Ni concentrations (Fig. 3d), which is not consistent with the high MgO, Cr and Ni contents of the Group 2 dikes. Thus, the high-Mg andesitic magmas parental to the Group 2 dikes could be the products of interaction between mantle peridotite and ascending intermediate to felsic melts originating from recycled crustal materials (Fig. 3d) (Kay & Kay, 1993; Yögodzinski *et al.*, 1994; Kelemen, 1995; Stern & Kilian, 1996; Xu *et al.*, 2002). Interaction of intermediate to felsic melts with mantle peridotite should enrich the melts in MgO, Cr and Ni (Fig. 3d), which is consistent with the observations. The mantle peridotite would have relatively high $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ values and low $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios, similar to the source of the Group 1 dikes. The low Nb

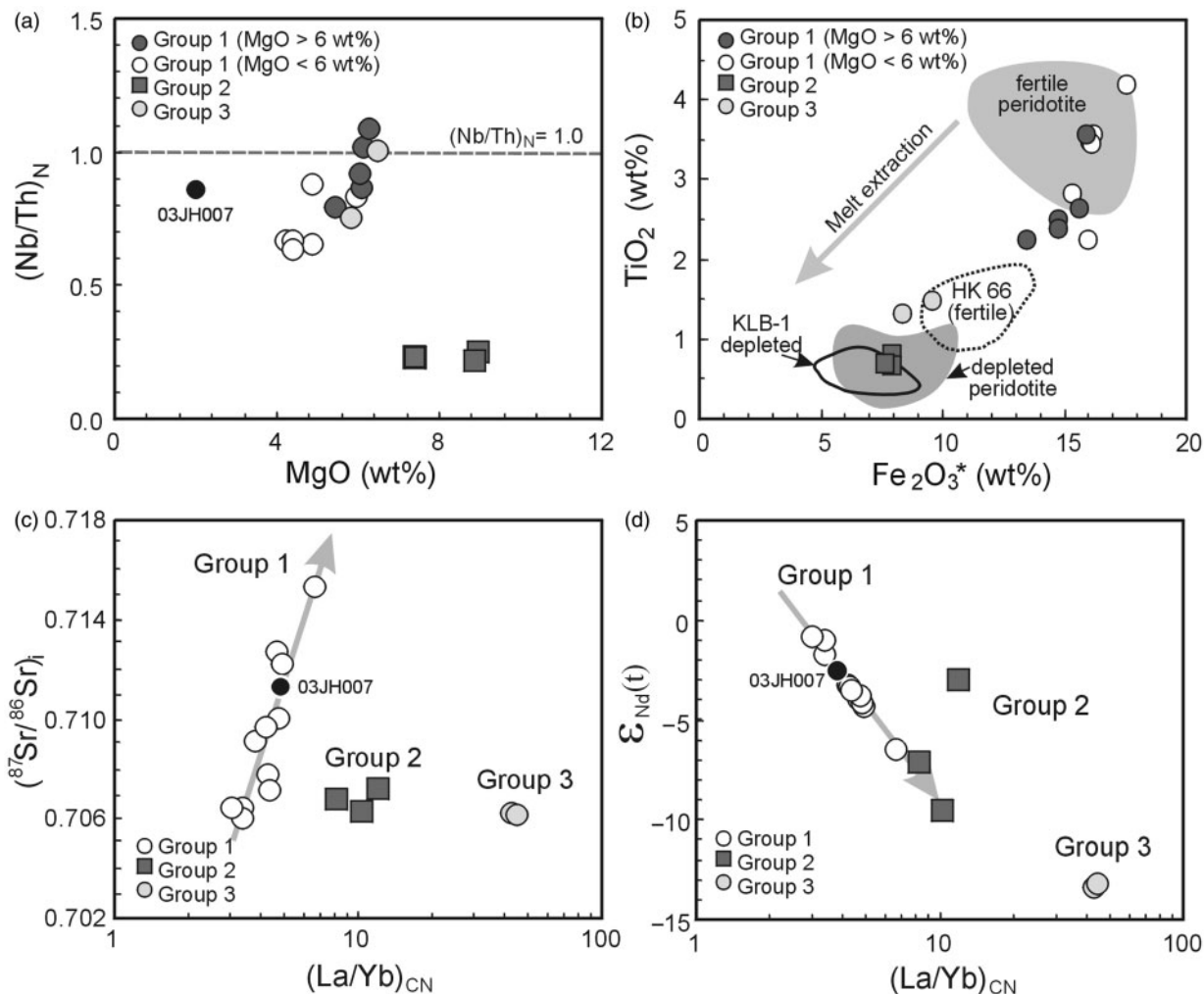


Fig. 9. (a) PM-normalized (Nb/Th) vs MgO, (b) TiO₂ vs Fe₂O₃* and (c) (⁸⁷Sr/⁸⁶Sr)_i and (d) ε_{Nd}(t) vs (La/Yb)_{CN} diagrams for mafic dikes from the Liaodong Peninsula. The PM and chondrite values are from Sun & McDonough (1989). In (b), the fields of peridotitic melts are after Falloon *et al.* (1988) and Hirose & Kushiro (1993).

and Ta contents of the Group 2 dikes, coupled with high Th/La ratios and low Nb/Th and (⁸⁷Sr/⁸⁶Sr)_i ratios (0.7063–0.7073) and ε_{Nd}(t) and ε_{Hf}(t) values, at intermediate silica contents, similar to those of lower crustal-derived xenoliths (Zheng *et al.*, 2004), indicate that the melts could have originated from a lower crustal source with low (⁸⁷Sr/⁸⁶Sr)_i, ε_{Nd}(t) (–3.0 to –9.5) and ε_{Hf}(t) (–3.2 to –10.1) values.

According to the experimental work of Rapp *et al.* (1999), the interaction of melts with mantle peridotite causes decreases in the SiO₂ and Al₂O₃ contents of the hybridized melts, with simultaneous increases in the contents of MgO, FeO, Na₂O, K₂O, TiO₂ and trace element abundances, but significantly, most element ratios (e.g. Sr/Y, La/Yb, Sr/Nd, Nb/La, K/La, etc.) remain nearly constant. Therefore, these ratios should reflect those of the parental

magmas to the Group 2 dikes. The parental magmas of Group 2 dikes have relatively high SiO₂ and Sr contents and low Y (15.8–17.3 ppm) and Yb (1.3–1.5 ppm) abundances, with high Sr/Y ratios similar to those of adakites (Defant & Drummond, 1990), indicating that these melts were derived by partial melting of recycled oceanic or continental crustal materials at high pressures, with garnet in the residue (Rapp *et al.*, 1999; Xu *et al.*, 2002). The (⁸⁷Sr/⁸⁶Sr)_i (>0.7060) and negative ε_{Nd}(t) values (<–9.5) of Group 2 dikes are distinct from those of partial melts of subducted oceanic slabs (ε_{Nd}(t) > 0; Defant & Drummond, 1990) and those of deeply subducted Yangtze continental crustal materials with high ε_{Nd}(t) values (>–3; eclogites; Jahn *et al.*, 2003), precluding subducted oceanic slab or subducted Yangtze crust being the source of the Group 2 dikes. However, the Sr, Nd and Hf isotopic compositions of the

intermediate to felsic parental magmas of the Group 2 dikes are similar to those of lower crustal-derived Late Triassic granodiorites and monzogranites in the Liaodong Peninsula (Fig. 7; Yang *et al.*, 2007a) and lower crustal-derived mafic granulite xenoliths (Zheng *et al.*, 2004), indicating that the crustal component in the origin of Group 2 dikes may be lower crust of the NCC. Thus, the Group 2 dikes with high-Mg andesitic compositions may have originated as melts of recycled NCC lower crust with subsequent interaction with mantle peridotite, as proposed by Kay & Kay (1993) and Xu *et al.* (2002).

Group 3

The geochemical and Sr–Nd–Hf isotopic compositions of the Group 3 dikes are distinct from those of Groups 1 and 2 (Figs 3–7), precluding a common source and petrogenesis. The Group 3 dikes have low SiO₂, MgO, Cr and Ni contents, distinct from those of Group 2 (Table 2 and Fig. 3). They have relatively low (⁸⁷Sr/⁸⁶Sr)_i and strongly negative ε_{Nd}(t) and ε_{Hf}(t) values, similar to those of Triassic nepheline syenites in the Liaodong Peninsula (Fig. 7a) and the worldwide lamproites and Group II kimberlites (Nowell *et al.*, 2004; Davies *et al.*, 2006), suggesting that they could be derived from a common source; for example, subcontinental lithospheric mantle (Nowell *et al.*, 2004; Davies *et al.*, 2006). In addition, the geochemistry of the Triassic nepheline syenites also suggests they were derived by partial melting of an enriched, refractory lithospheric mantle source (mica- or amphibole–pyroxene-bearing harzburgite) beneath the NCC (Wu *et al.*, 2006b). The Group 3 dikes have low TiO₂ and total Fe₂O₃ concentrations, similar to those of experimental melts derived from partial melting of a relatively refractory mantle (harzburgite) source (KLB-1; Hirose & Kushiro, 1993; Hirose, 1997; refractory peridotite; Falloon *et al.*, 1988) (Fig. 9b). As partial melts of refractory peridotite should have low CaO and Al₂O₃ concentrations, the high Al₂O₃ concentrations of the Group 3 dikes may be the result of melting of pyroxene veins in harzburgite (Foley, 1992). Their shoshonitic characteristics, with high K contents, indicate a K-bearing phase, such as amphibole or phlogopite in their source. Melts in equilibrium with phlogopite are expected to have higher Rb/Sr (>0.1) and lower Ba/Rb (<20) ratios than those from amphibole-bearing sources (Furman & Graham, 1999). In Fig. 10b, the Group 3 dikes display high Ba/Rb (>30) and low Rb/Sr (<0.1), suggesting an amphibole-bearing source. Thus, the Group 3 dikes could have been derived from an amphibole-bearing, refractory lithospheric mantle source that was metasomatized by recycled crustal materials prior to magma generation.

The Group 3 dikes are enriched in LILE and LREE and depleted in Nb and Ta, with negative Nb, Ta and Ti anomalies in PM-normalized trace element patterns (Fig. 6b), suggesting that metasomatism of the source was

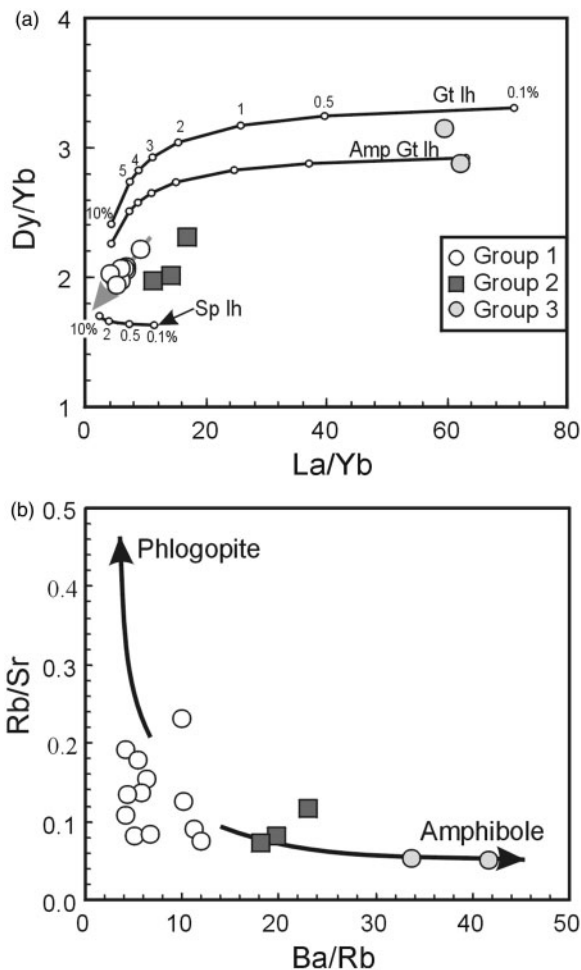


Fig. 10. (a) Dy/Yb vs La/Yb plot illustrating geochemical modeling results. Non-modal, point-average fractional partial melting curves are presented for garnet lherzolite (Gt lh), garnet-facies amphibole lherzolite (Amp Gt lh) and spinel lherzolite (Sp lh). Mineral assemblages, normative weight fractions of minerals (*i*) in the partial melts, and mineral–melt distribution coefficients (*D*) used for geochemical modeling are listed below. Source compositions are PM values of Sun & McDonough (1989); *D* values are from <http://earthref.org/database>. (b) Plot of Rb/Sr vs Ba/Rb for the mafic dikes from the Liaodong Peninsula.

Minerals	Ol	Opx	Cpx	Gt	Sp	Phl	Amp
Gt lh	0.5	0.3	0.15	0.05			
melt mode	0.05	0.2	0.3	0.45			
Amp Gt lh	0.5	0.31	0.1	0.05			0.04
melt mode	0.17	0.19	0.27	0.02			0.35
Sp lh	0.5	0.35	0.1		0.05		
melt mode	0.2	0.3	0.38		0.1		0.05
<i>D</i> _{La}	0.0028	0.008	0.0020	0.0014	0.01	0.0004	0.016
<i>D</i> _{Dy}	0.007	0.022	0.330	1.06	0.01	0.029	0.78
<i>D</i> _{Yb}	0.0015	0.042	0.280	4.01	0.01	0.03	0.22

triggered by subduction-related fluids or melts. Niobium is depleted relative to the LREE, and negative Nb, Ta, Zr and Hf anomalies in the PM-normalized trace element diagram (Fig. 6b), together with low $\epsilon_{\text{Nd}}(t)$ values and relatively high LILE/HREE and LILE/HFSE, are commonly interpreted to be the result of addition of subduction-related fluids and melts to a refractory mantle source (Kepezhinskis *et al.*, 1997).

The Group 3 dikes are relatively depleted in HREE compared with LREE. They have extremely high (La/Yb)_{CN} and (Gd/Yb)_{CN} ratios (Table 3), combined with low HREE abundances (Fig. 5b). Based on geochemical modeling, small-degree partial melts from an amphibole–garnet peridotite ought to have relatively high La/Yb and low Dy/Yb (Fig. 10a). The Group 3 dikes show decoupled Nd [$\epsilon_{\text{Nd}}(t) \sim -13$] and Hf [$\epsilon_{\text{Hf}}(t) \sim -11.5$] isotopic compositions with $\Delta\epsilon_{\text{Hf}} > 0$ (Table 4), indicating an ancient source in the garnet stability field. Despite the effects of parent/daughter ratio fractionation during the partial melting event that produced the Group 3 dikes, calculated depleted mantle model ages for Nd and Hf are consistently ancient in the range of 1.86–1.58 Ga. The Sr–Nd–Hf isotopic characteristics, therefore, suggest that the Group 3 dikes were derived from a mantle source characterized by long-term LREE enrichment and weak to moderate Rb/Sr enrichment. As the relative order of partition coefficients for Lu–Hf–Sm–Nd in pyrope (and majoritic) garnet is $D_{\text{Sm}} > D_{\text{Nd}}$, $D_{\text{Lu}} > D_{\text{Hf}}$ and $I_{\text{Hf}} > D_{\text{Nd}}$, extraction of melt within the garnet stability field will lead to residual peridotite compositions that evolve rapidly with time to radiogenic Hf and Nd isotopic compositions above the mantle Nd–Hf isotope array, and thus, to positive $\Delta\epsilon_{\text{Hf}}$ values. Therefore, these characteristics, including relatively high (La/Yb)_{CN} (42.7–44.6) and (Dy/Yb)_{CN} (1.9–2.0) ratios (Table 2), relatively steep MREE to HREE patterns (Fig. 5b) and decoupled Nd and Hf isotopic compositions, are garnet signatures (Kay & Gast, 1973; Salters & Hart, 1989; Hirschmann & Stolper, 1996), indicating that the Group 3 dikes may have formed by relatively low-percentage melting of an amphibole-bearing mantle source in the garnet stability field.

In summary, geochemical and Sr–Nd–Hf isotopic compositions of the Late Triassic mafic dikes in the Liaodong Peninsula suggest that at least four components were involved in their petrogenesis (i.e. asthenospheric mantle, lithospheric mantle, upper crust and foundered lower crust). The Group 1 dikes were most probably produced by partial melting of a depleted, asthenospheric mantle source, with subsequent crustal assimilation and fractional crystallization during magma ascent and emplacement. The Group 2 dikes may have originated as melts of foundered NCC lower crust with subsequent interaction of the melts with mantle peridotite. In contrast, the Group 3

dikes were possibly generated by partial melting of enriched lithospheric mantle with garnet in the residue.

Tectonic implications

Mafic dike swarms are a common expression of magma generation associated with extension in a post-collisional continental tectonic setting (e.g. Rock, 1991). Together with the presence of Late Triassic alkaline to calc-alkaline intrusions (Chen *et al.*, 2003; Guo *et al.*, 2005; Yang *et al.*, 2005, 2007a), the mafic dikes of the Liaodong Peninsula suggest that the Sulu orogenic belt underwent extension during the Late Triassic. As discussed in previous sections, the parental magma of the Group 1 dikes was derived by partial melting of asthenospheric mantle and experienced upper crustal assimilation and fractional crystallization. In contrast, the Group 2 dikes originated from interaction of foundered NCC lower crustal-derived melts with mantle peridotite, whereas the Group 3 dikes were derived from partial melting of enriched, refractory lithospheric mantle that experienced some fractional crystallization. Residual garnet is not required to generate the trace element characteristics and Nd–Hf isotopic correlations of the Group 1 dikes, and thus the pressure of melt generation is constrained in the region of the spinel facies. However, the trace element characteristics of the Group 2 and 3 dikes, with decoupled Nd and Hf isotope compositions, require garnet in the residue, indicating that the depth of melt generation was in the garnet stability field.

Two alternative geodynamic models have been proposed to explain Late Triassic magmatism within the Dabie–Sulu orogenic belt. (1) In the slab break-off model, the leading portions of high-density oceanic lithosphere founder and result in buoyancy-driven uplift and exhumation of the UHP metamorphic rocks within low-density slices, accompanied by normal faulting of the hanging-wall plate, with crustal extension and magmatism (Ernst & Liou, 1995; Chen *et al.*, 2003). (2) In the lithospheric delamination model, continent–continent collision leads to thickening of the lithosphere, including the lower continental crust. Depending on the extent of the pressure increase, lower crustal mafic paragneiss may be transformed to amphibolite ($P < 1$ GPa) or to granulite–eclogite–garnet clinopyroxene assemblages at higher pressures (~ 2 –3 GPa; e.g. Wolf & Wyllie, 1994; Rapp & Watson, 1995). The density increase leads to gravitational instability of an over-thickened lithospheric keel. In particular, dense garnet-rich lower crustal restite allows for detachment of the lithospheric mantle from the upper lithosphere and leads to its sinking into the asthenosphere (Bird, 1979; England & Houseman, 1989; Houseman & England, 1993; Lustrino, 2005). In this case, the change in potential energy in the remaining lithosphere would lead to a sudden uplift of the Sulu orogen and surrounding areas (e.g. Bird, 1979; England & Houseman, 1989; Houseman & England, 1993) with crustal extension and Late Triassic magmatism

(as suggested by Kay & Kay, 1993; Lustrino, 2005; Yang *et al.*, 2005, 2006b).

The slab break-off model can explain the exhumation of UHP rocks from mantle depths to crustal levels (Davies & von Blanckenburg, 1995; Ernst & Liou, 1995) and a four-component source for the Late Triassic dolerite dikes (Gorring & Kay, 2001; Gorring *et al.*, 2003). In the slab break-off model, resultant upwelling of the asthenosphere would heat the overlying lithosphere and lead to melting of the metasomatized and hydrated portions of the lithospheric mantle, which would in turn result in alkaline to ultrapotassic magmas by small degrees of melting or calc-alkaline magmas by larger degrees of melting (Davies & von Blanckenburg, 1995). However, it cannot explain the fact that the depth of partial melting of the asthenospheric mantle was at shallow levels in the spinel stability field, whereas the depth of partial melting of lithospheric mantle was in the region of garnet stability. In addition, magma generation requires break-off to occur at shallow depths, thus causing significant thermal perturbation capable of melting metasomatized or hydrated peridotite that has a solidus temperature of $\sim 1100^{\circ}\text{C}$ at 80 km depth (Davies & von Blanckenburg, 1995). In the Sulu orogenic belt, where continental subduction extended to >200 km depth (Ye *et al.*, 2000), slab break-off would need to be at such great depth that it would have led to negligible thermal perturbation in the overriding lithosphere and hence no magmatism (Davies & von Blanckenburg, 1995). Furthermore, detailed zircon and monazite SHRIMP U–Pb dating and inferred P – T paths of the metamorphic rocks show that UHP metamorphism occurred between 244 and 226 Ma, followed by retrograde metamorphism at 221–218 Ma, during exhumation to at least mid-crustal levels (Liu *et al.*, 2004; Wan *et al.*, 2005). All these data indicate that the protoliths of the UHP metamorphic rocks were subducted to mantle depths in the Early–Middle Triassic (before ~ 226 Ma) and rapidly exhumed to mid-crustal levels by ~ 218 Ma.

The slab break-off model is commonly used to explain the initial stage of rapid exhumation of the UHP metamorphic rocks (at about 244–226 Ma), as proposed by Davies & von Blanckenburg (1995) and Ernst & Liou (1995). However, the emplacement ages of the Late Triassic magmatic rocks [215–200 Ma for syenites in the Sulu orogenic belt (Guo *et al.*, 2005; Yang *et al.*, 2005) and 213–212 Ma for dolerite dikes and monzogranites in the Liaodong Peninsula (Yang *et al.*, 2007a; this study)] indicate that magmatism significantly post-dates the 240–226 Ma collision between the North China and Yangtze cratons and ultrahigh-pressure metamorphism (e.g. Chavagnac & Jahn, 1996; Hacker *et al.*, 1998; Liu *et al.*, 2004; Wan *et al.*, 2005).

An alternative hypothesis is that lithospheric delamination, accompanied by crustal extension, was induced by

instability of the thickened lithosphere (Houseman *et al.*, 1981). The change in potential energy in the remaining lithosphere would then lead to a sudden uplift of the Sulu orogen and surrounding areas (e.g. Bird, 1979; England & Houseman, 1989; Houseman & England, 1993). This is supported by the zircon U–Pb and single mineral Sm–Nd and Rb–Sr isotope geochronology of ultrahigh-pressure metamorphic rocks and adjacent country rocks, which distinguish two stages of rapid cooling corresponding to two stages of fast uplift: an initial period of rapid uplift and cooling between 226 and 218 Ma that could be caused by continental subduction or slab break-off, and a later period of rapid cooling that could be caused by partial delamination or convective removal of lithospheric mantle and related extension during the Late Triassic to Middle Jurassic (218–173 Ma) (Li *et al.*, 2000; Liu *et al.*, 2004; Wan *et al.*, 2005).

Furthermore, the delamination model can also explain the geochemical and isotopic variations in the Late Triassic dolerite dikes in the Liaodong Peninsula. The geochemical and geochronological data presented here favor four source components that can be explained as a fertile asthenosphere, a re-enriched, refractory lithospheric mantle, a detached lower crust and an upper crustal component. Our preferred model for the petrogenesis of the Late Triassic doleritic magmas and their relationship to the regional tectonic evolution is shown in Fig. 11. Subduction of the Yangtze Craton beneath the North China Craton forced down lower crustal rocks into the mantle (Fig. 11a) at about ~ 245 Ma (Cong, 1996; Hacker *et al.*, 1998; Liu *et al.*, 2004; Wan *et al.*, 2005). Oceanic slab break-off caused the UHP–HP rocks to be rapidly exhumed between 244 and 226 Ma and taken to middle levels at about 221–218 Ma (Fig. 11b) (Davies & von Blanckenburg, 1995; Ernst & Liou, 1995; Liu *et al.*, 2004; Wan *et al.*, 2005). Continent–continent collision had thickened the lithosphere of the Sulu orogenic belt and surrounding areas, and this induced mafic lower crust transformation to high-density eclogite or garnet clinopyroxenite. The density increase led to gravitational instability of an over-thickened lithospheric keel and induced detachment of the lithospheric mantle from the upper lithosphere and subsequent sinking into the asthenosphere (Bird, 1979; England & Houseman, 1989; Houseman & England, 1993; Lustrino, 2005). The change in potential energy in the remaining lithosphere would then lead to a sudden uplift of the Sulu orogen and surrounding areas, accompanied by crustal extension (e.g. Bird, 1979; England & Houseman, 1989; Houseman & England, 1993; Kay & Kay, 1993; Lustrino, 2005). The volume formerly occupied by the lithospheric keel was replaced by new, fertile asthenosphere, which underwent decompressional melting during upwelling. Asthenosphere-derived melts assimilated crustal materials during their ascent and formed the Group 1

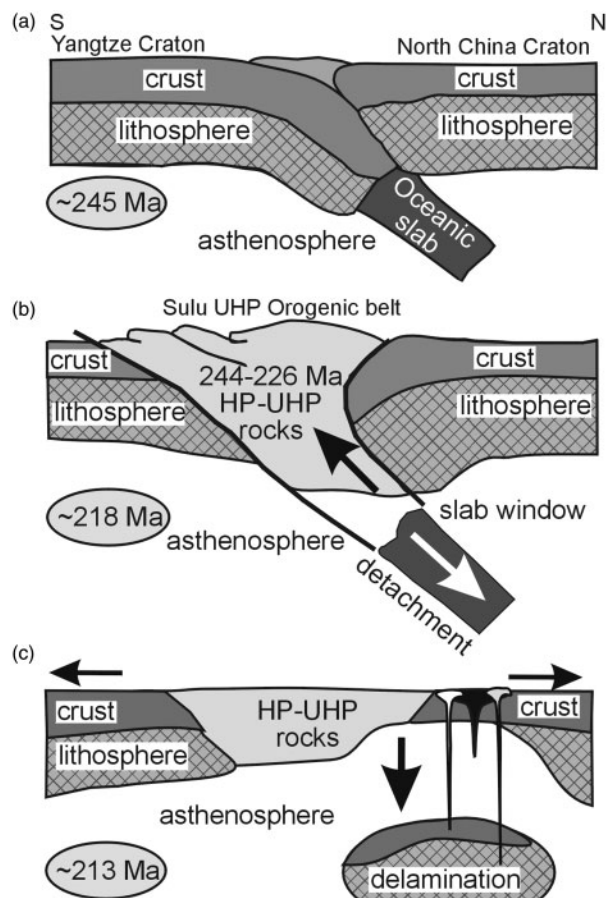


Fig. 11. Schematic illustration showing the burial and exhumation of the UHP rocks of the Dabie–Sulu belt, accompanied by melting of upwelling asthenosphere and delamination of lithosphere. (a) Northward subduction of the Yangtze Craton commenced below the North China Craton at about 245 Ma. UHP mineral assemblages started to form at mantle depths. (b) As a result of slab break-off of the eclogitized oceanic lithosphere, the UHP–HP rocks were rapidly exhumed between 244 and 226 Ma and taken to mid-crustal levels at about 221–218 Ma. (c) Instability of the thickened lithosphere induced delamination. Partial melting of upwelling asthenospheric mantle and delamination of lithospheric mantle and some lower crust allowed production of the various Liaodong Peninsula dikes. (a) and (b) are modified after Jahn *et al.* (1999) with new published geochronological data of Liu *et al.* (2004) and Wan *et al.* (2005).

dikes in the Liaodong Peninsula at ~213 Ma. The partial melts of delaminated lower crust and enriched, refractory lithospheric mantle interacted with asthenospheric peridotite and produced the coeval Group 2 dikes with high-Mg andesitic compositions and the Group 3 dikes with shoshonitic signatures (Fig. 11c).

CONCLUSIONS

Three suites of dolerite dikes in the Liaodong Peninsula of the northeastern North China Craton have distinct

geochemical and Sr–Nd–Hf isotopic compositions, indicating they were derived from discrete sources by various petrogenetic processes. The Group 1 dikes, with low SiO₂, intermediate MgO concentrations, high total Fe₂O₃ and TiO₂ contents, and weak to negligible negative Nb and Ta anomalies, formed by crustal assimilation and fractional crystallization of mafic magmas derived from partial melting of a fertile asthenospheric mantle source in the spinel stability field. The Group 2 dikes, with geochemical signatures of high-Mg andesites, were the result of interaction between melts derived from partial melting of delaminated lower crust and asthenospheric peridotite. The Group 3 shoshonitic dikes originated from partial melting of an ancient, refractory lithospheric mantle source at high pressures with garnet in the residue. The zircon U–Pb ages of the dolerite dikes in the Liaodong Peninsula indicate that they intruded at ~213 Ma, post-dating the collision of the North China and Yangtze cratons and the UHP metamorphism. Late Triassic magmatism is probably related to lithospheric delamination following continent–continent collision.

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