Geochemistry of Early Cretaceous Intermediate to Mafic Dikes in the Jiaodong Peninsula: Constraints on Mantle Source Composition beneath Eastern China

Qun Long,1 Rong Hu,2 Yi-Zeng Yang,1,* Chun-Yue Yang,1 Shu Zhou,1 Wolfgang Siebel,3 and Fukun Chen1

1. School of Earth and Space Sciences, University of Science and Technology of China, Hefei, 230026, China; 2. College of Resources and Environment, Yangtze University, Wuhan, 430100, China; 3. Department of Earth and Environmental Sciences, Albert-Ludwig University Freiburg, 79104 Freiburg, Germany

ABSTRACT

The Jiaodong Peninsula of eastern Shandong Province comprises the Jiaobei terrain of North China affinity and the Sulu ultrahigh-pressure metamorphic terrain. In this study, we present zircon U-Pb ages, major- and trace-element data, and Sr-Nd-Pb isotopic compositions of intermediate to mafic dikes from the Linglong region of the Jiaobei terrain and the Rushan region of the Sulu terrain to discuss the nature of the mantle source(s) beneath eastern China during the Early Cretaceous. Zircon U-Pb dating yields Early Cretaceous dike emplacement ages ranging from ∼124 to ∼120 Ma for the Linglong region and from ∼118 to ∼108 Ma for the Rushan region. Dikes from both regions are all potassic, with “arc-like” trace-element distributions as well as high unradiogenic Pb isotopic composition, low initial εNd values [−19.64 to −10.80], and high radiogenic 87Sr/86Sr ratios (0.7075–0.7112), suggesting the involvement of an extensively enriched mantle component. Such isotopic characteristics are found in contemporaneous intermediate to mafic intrusive rocks in the whole Shandong Province and are explained in terms of a Triassic northwestward-subduction model of the Yangtze Block beneath the North China Block. The dikes from the Linglong and Rushan regions have low Nb/U and Ce/Pb ratios, implying the involvement of upper-continental-crustal material. Combined with the southward younging of zircon U-Pb ages through Shandong Province, we suppose that the enriched mantle source beneath the Jiaodong Peninsula was formed by metasomatism of silicic melts or fluids derived from the subducted Yangtze continental crust during the Triassic, followed by decompression melting of this mantle during the Early Cretaceous due to rollback of the subducted Paleo-Pacific plate.

Online enhancements: supplemental tables.

Introduction

The Jiaodong Peninsula [fig. 1a], located in eastern Shandong Province, defines the southeastern margin of the North China Craton [NCC]. The NCC is bounded by the Central Asian Orogenic Belt in the north and the Qinling-Dabie-Sulu orogenic belt in the south. The Paleozoic Kimberlites of Mengyin and Fuxian suggest that the subcontinental lithospheric mantle beneath the NCC is thick [180–200 km], cold, and refractory, similar to other Archean cratons [Menzies et al. 1993; Griffin et al. 1998]. On the other hand, Cenozoic basalts and their xenoliths suggest hot and fertile mantle sources, pointing to a rather thin lithosphere [Xu 2001; Wu et al. 2003, 2006; Zheng et al. 2007; Li et al. 2016]. Geochemical and geophysical studies show that the eastern part of the NCC is currently characterized by high surface heat flow, intensive structural deformation, and low seismic-wave velocities in the upper mantle [Griffin et al. 1998; Xu 2001; Wu et al. 2005; Yang et al. 2007; Zheng et al. 2007; B. Chen et al. 2008a; L. Chen et al. 2008b; Chen 2010; Zhu et al. 2012b]. Petrological and geochemical evidence from xenocrysts record a long-term and very complicated evolution history of lithospheric thinning beneath eastern China [e.g.,
Several important geological events took place in Shandong Province during the Mesozoic. These include the formation of fault-controlled basins and large-scale magmatism and mineralization processes, as well as large-scale thinning of the lithospheric mantle (Zhang et al. 2002, 2003; Deng et al. 2007; Zhu et al. 2008; Gu et al. 2013; Lin et al. 2013; Yang et al. 2014a). Knowledge about the nature and evolution of the lithospheric mantle can give important clues about these geological events. Although numerous papers have already discussed the petrology and geochemistry of xenoliths from mantle peridotites or mantle-derived intrusive rocks in the NCC (e.g., Gao et al. 2002; Zhang et al. 2002, 2008; Wu et al. 2006; Xu et al. 2010) and the Dabie-Sulu orogen (e.g., Jahn et al. 1999; Wang et al. 2005; Liu et al. 2008b; Tang et al. 2009; Chen et al. 2011; Xu et al. 2012; Ma et al. 2014b; Cai et al. 2015), direct information about the mantle beneath the southeastern margin of the NCC during the Early Cretaceous cannot be easily reconciled, because of the scarcity of material that comes from the mantle. However, Early Cretaceous mafic dikes are widely distributed in the Jiaodong Peninsula (Yang et al. 2004; Cai et al. 2013). These dikes originated from mantle sources, and thus their geochemical composition can provide impor-

Figure 1.  

(a), Simplified geological map of the North China Craton and its surroundings (modified after Zhao et al. 2005). (b), Simplified geological map of the Jiaodong Peninsula (modified after Yang et al. 2012b). (c), Geological map of the Rushan region, Sulu terrain, showing sample localities. (d), Geological map of the Linglong region, Jiaobei terrain, showing sample localities. Maps in (c) and (d) are modified after the 1:200,000 geological map of China. UHP = ultrahigh-pressure.
tient information about this reservoir and help to improve the understanding of the geological processes during the late Mesozoic in this region (Halls 1982, 1987; Zhang et al. 2011; Cai et al. 2013, 2015).

Jiaodong is an ideal place to study the interaction and modification of mantle metasomatism because the peninsula is underlain by different tectonic units, including Precambrian basement rocks within the Jiaobei terrain as part of the NCC in the north and high-pressure (HP) to ultrahigh-pressure (UHP) rocks within the Sulu terrain in the south (fig. 1b). The Jiaobei terrain is located in the southeastern part of the Archean NCC, while the Sulu terrain belongs to the eastern part of the famous Dabie-Sulu HP to UHP metamorphic belt. Early Cretaceous mafic dike swarms, including lamprophyres, diabases, and diorites, are developed in the Jiaodong Peninsula. They intruded the Precambrian basement, Mesozoic magmatic rocks, and gold deposits of the Jiaodong province (Yang et al. 2004; Liu et al. 2006, 2008a, 2008b, 2009a, 2009b, 2012, 2013a, 2013b, 2015; Cai et al. 2013, 2015; Ma et al. 2014a, 2014b, 2016).

In this study, intermediate to mafic dikes were sampled from the Linglong region of the Jiaobei terrain and the Rushan region of the Sulu terrain and analyzed with geochemical and geochronological methods. The main reasons for this approach are (1) to reconstruct the geochemical characteristics of the magma source(s), (2) to provide better understanding of the tectonic evolution of the Jiaodong Peninsula, and (3) to elucidate the differences in mantle source composition between the eastern and western parts of the Jiaodong Peninsula.

Geological Setting

The Jiaobei and Sulu terrains are separated by the Wulian-Yantai fault (fig. 1). The Jiaobei terrain belongs to the NCC and consists of Precambrian basement rocks (Zhai et al. 2000; Zhai and Santosh 2011), Mesozoic granitoids (Jiang et al. 2012; Yang et al. 2012b; Ma et al. 2013; Wang et al. 2014), bimodal volcanic rocks (Fan et al. 2001), and intermediate to mafic dikes (Yang et al. 2004; Liu et al. 2009a; Cai et al. 2013; Ma et al. 2014b). The Precambrian basement is mainly composed of the Neoarchean Jiaodong Group, which contains amphibolite- to granulite-facies volcanic and sedimentary sequences, while the Paleoproterozoic Jingshan and Fenzishan Groups consist of gneiss-chert- to amphibolite-facies metasedimentary sequences, and the Neoproterozoic Penglai Group contains low-grade metamorphosed sedimentary sequences (e.g., Zhang et al. 2003; Tang et al. 2007; Li et al. 2007a; Jahn et al. 2008). Mesozoic granites of the Jiaobei terrain mainly include the Late Jurassic Linglong biotite granite and the Luanshan monzogranite (~160–157 Ma), the Early Cretaceous Guojialing granodiorite (~130–125 Ma; Yang et al. 2012b), and the Early Cretaceous Aishan monzogranite (~116 Ma; Goss et al. 2010). Early Cretaceous volcanism took place along the whole Jiaodong Peninsula between Yantai and Rushan (fig. 1b). The volcanism was bimodal in character (Fan et al. 2001), and the mafic and silicic rocks were considered melting products of metasomatically enriched lithosphere and ancient lower crust, respectively (Kuang et al. 2012). The Linglong region is located in the north of the Jiaobei terrain and hosts economically important deposits of the Jiaodong gold province. The Early Cretaceous intermediate to mafic dikes are often associated with these gold deposits and are crosscut by auriferous quartz veins.

The Sulu terrain is the easternmost part of the Dabie-Sulu HP to UHP metamorphic belt formed by the collision of the South China (Yangtze) Craton and the NCC during the Triassic (Zhai et al. 2000; Zhang et al. 2002, 2003; Zheng et al. 2003). Diamond- and coesite-bearing xenoliths in both eclogites and wall-rock gneisses suggest that parts of the subducted South China Block reached depths of c. 120 km before rapid resurfacing (Wang et al. 1989; Xu et al. 1992; Ye et al. 2000). From northwest to southeast, the Sulu orogen can be divided into four zones: an orthogneiss UHP unit, a supracrustal UHP unit, a kyanite-bearing quartzite-marble HP unit, and a paragneiss-schist HP unit (Liu et al. 2004a). The exposed rocks in the Sulu belt mainly consist of granitic gneisses and Mesozoic igneous rocks, different types of eclogites, retrograde eclogites, amphibolites, and some ultramafic xenoliths. Protoliths of the granitic gneisses are mainly biotite monzogranites and granodiorites of Neoproterozoic age (~800–700 Ma; Zheng et al. 2004; Li et al. 2007b; Zeng et al. 2014). The Mesozoic magmatism can be divided into three stages: Late Triassic (225–205 Ma), Late Jurassic (160–150 Ma), and Early Cretaceous (130–110 Ma; e.g., Guo et al. 2005). Late Triassic alkaline rocks are exposed only in the eastern part of the Sulu terrain, including the Jiaozishan syenite, the Xingjia gabbro, and the Chashan syenite (Chen et al. 2003; Yang et al. 2005). Late Jurassic granitoids occur in the northeastern part of the Sulu terrain, including two large intrusions: the Wendeng and Kunyushan plutons (Hu et al. 2007). Early Cretaceous magmatic rocks include the Weidieshan and Sanfoshan plutons (Guo et al. 2005; Goss et al. 2010). The Rushan region in the Sulu terrain is also an important metallogenic belt. The Early Cretaceous intermediate to mafic dikes in the Rushan region are
concentrated along NNE-striking fault zones or form intrusive sheets within the Mesozoic granites.

**Samples and Petrography**

Eighteen dike samples from the Linglong region (fig. 1c) and 11 samples from the Rushan region (fig. 1b) were collected for analysis. Most of the dikes are NE/NNE trending. They were emplaced along fault zones of similar orientation (fig. 2a). In several outcrops, up to five or six dikes are exposed. They range from intermediate (andesite) to mafic (alkaline lamprophyric) in composition, with thicknesses ranging from 0.2 m to several meters.

Intermediate dikes have hypidiomorphic inequigranular and massive texture. A representative sample is shown in figure 2b. Sample LL-11 is composed of ∼5 vol% pyroxene, ∼30 vol% hornblende, and ∼65 vol% plagioclase. Sample LL-5 is composed of ∼25 vol% biotite, ∼5 vol% hornblende, ∼65 vol% plagioclase, and ∼5 vol% opaque minerals. Sample LL-1 consists of ∼40 vol% hornblende, ∼55 vol% plagioclase, and ∼5 vol% opaque minerals.

The intermediate dikes are commonly dense, fine-grained, and massive and show porphyritic texture; most of the phenocrysts are hornblende set in a matrix of plagioclase. A representative diorite porphyry sample is shown in figure 2c. Sample SL-5 is composed of ∼25 vol% prismatic or rhombic hornblende and ∼75 vol% plagioclase; sample SL-2 has ∼40 vol% hornblende and ∼60 vol% plagioclase. Phenocrysts (∼20 vol%) mainly consist of euhedral and coarse-grained hornblende.

The alkaline lamprophyres show porphyritic texture. Phenocrysts consist of hornblende and small amounts of olivine. A representative sample is shown in figure 2d. Sample SL-1 is composed of ∼25 vol% hornblende and ∼75 vol% plagioclase; sample SL-2 has ∼40 vol% hornblende and ∼60 vol% plagioclase. Phenocrysts (∼20 vol%) mainly consist of euhedral and coarse-grained hornblende.

**Figure 2.** a, Contact relationship of intermediate to mafic dikes with wall rock [Mesozoic granite] in the Linglong region. b, Photomicrograph of intermediate dike [sample LL-11]. c, Photomicrograph of intermediate porphyry dike [sample SL-5]. d, Photomicrograph of lamprophyre dike [sample SL-1]. Hbl = hornblende; Ol = olivine; Pl = plagioclase; Px = pyroxene.
in figure 2d. Sample SL-1 is composed of ~30 vol% hornblende, ~65 vol% plagioclase, and ~5 vol% opaque minerals. Hornblende is needle shaped or prismatic and locally altered by hydrothermal fluids.

**Analytical Methods**

Zircon grains were separated from crushed rock with standard density and magnetic-separation techniques and selected under a binocular microscope through handpicking. About 100–200 grains from each sample were mounted in epoxy resin and then polished for analysis and photographed under reflected and transmitted light. Zircon grains were imaged by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the University of Science and Technology of China (USTC). Zircon 91500 was used as an external calibration standard for age calculation, and NIST610 was analyzed twice per 10 analyses for concentration calculations of U, Th, and Pb. More details on the U-Pb analytical techniques are given in Liu et al. (2007). U-Pb isotope ratios were calculated with Isoplot (Ludwig 2003). All ages were calculated with the software Glitter, version 4 (Macquarie University, Sydney, Australia), and U-Pb isotopic ratios are given in Liu et al. (2007). U-Pb isotopic ratios were calculated by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the University of Science and Technology of China (USTC). Zircon U-Pb dating was accomplished by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the University of Science and Technology of China (USTC). Zircon U-Pb dating was accomplished by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the University of Science and Technology of China (USTC). Zircon U-Pb dating was accomplished by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the University of Science and Technology of China (USTC). Zircon U-Pb dating was accomplished by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the University of Science and Technology of China (USTC).

For whole-rock major- and trace-element and isotopic analysis, rock samples were crushed and powdered to less than 10 μm. Major elements were analyzed by X-ray fluorescence at IGG CAS. Loss on ignition was determined after igniting the sample powder at 1000ºC for 1 h. From repeated sample runs the reproducibility of major-element concentrations was estimated to be better than 5% (±σ). Trace-element abundances were determined by ICP-MS with an Agilent 7500a at the USTC.

Rb-Sr, Sm-Nd, and Pb isotopic analyses of whole-rock samples were carried out at the Laboratory for Radiogenic Isotope Geochemistry, USTC. Rb, Sr, and light rare earth elements (LREEs) were isolated and purified on quartz columns by conventional ion exchange chromatography with a 5-mL bed of AG 50 W-X12 resin (200–400 mesh). Nd, Sm, and other REEs were separated from each other on quartz columns, with 1.7 mL Teflon powder coated with HDEHP (di-[2-ethylhexyl]orthophosphoric acid) as cation exchange medium. Sr was loaded with a Ta-HF activator on preconditioned Ta filaments. Nd was loaded as phosphate on preconditioned Re filaments. Pb was leached from the solutions and then purified twice through AG1-x8 resin. Rb, Sr, Sm, Nd, and Pb isotopic measurements were carried out on a Finnigan MAT-262 thermal ionization mass spectrometer at the USTC. Sr and Nd isotopic ratios were corrected for mass fractionation relative to $^{87}Sr/^{86}Sr$ of 0.1194 and $^{146}Nd/^{144}Nd$ of 0.7219, respectively. Precision of the measured Pb isotopic ratios was better than 0.01%. Further details of the analytical procedures are given in Chen et al. (2000, 2007).

**Analytical Results**

**Zircon U-Pb Ages.** Six intermediate to mafic dikes (samples SL-4, SL-6, SL-7, SL-11, LL-8, and LL-11) from the Linglong and Rushan regions were selected for LA-ICP-MS zircon U-Pb dating (fig. 3). Analytical results are given in table S1 (tables S1–S3 available online).

Most zircons from these dikes are euhedral or subhedral, with grain sizes ranging from 50 to 250 μm and length-width ratios from 1:1 to 4:1. All grains are transparent or yellowish and generally prismatic and show magnatic oscillatory zoning in CL images (fig. 3a). Th/U ratios of the zircons range from 0.08 to 3.25, mostly >0.3, which is a common range for magnatic zircon.

Thirty-two analyses were made on sample SL-4, yielding a weighted mean 206Pb/238U age of 112.4 ± 1.1 Ma. Sample SL-6 gives a weighted mean 206Pb/238U age of 118.2 ± 3.3 Ma (n = 7). Two analyses give older (inherited) Neoproterozoic ages of 703 and 773 Ma. Sample SL-7 gives a weighted mean 206Pb/238U age of 112.2 ± 1.7 Ma (n = 25). Sample SL-11 gives a weighted mean 206Pb/238U age of 107.6 ± 1.6 Ma (n = 23; fig. 3b), and sample LL-8 yields a weighted mean 206Pb/238U age of 123.5 ± 4.6 Ma (n = 10). Ten analyses on sample SL-11 give a weighted mean 206Pb/238U age of 121.3 ± 3.8 Ma. Altogether, the ages confirm that the dikes in the Jiaodong Peninsula were emplaced during the Cretaceous.

**Major and Trace Elements.** Major- and trace-element data from the dikes in the Linglong and Rushan regions are given in table S2. The dikes from the Linglong region have low SiO₂ (44.53–55.05 wt%) and high MgO (6.77–13.26 wt%) contents, with Mg# ranging from 64 to 73. High K₂O contents (1.5–4.4 wt%) result in high K₂O/Na₂O ratios (0.60–1.82). Cr and Ni contents range from 383 to 818 ppm and from 135 to 328 ppm, respectively. In the total alkalai–versus-silica (TAS) diagram, they plot within the gabbro fields (fig. 4a).

Compared to those from Linglong, the dikes from the Rushan region have more variable SiO₂ (45.54–
60.66 wt %) and MgO (3.15–12.73 wt %) contents, with Mg# ranging from 58 to 76. They have high K2O content (1.3–4.4 wt %), with K2O/Na2O ratios between 0.47 and 1.71. Their Cr and Ni concentrations vary from 108 to 1176 ppm and from 18.5 to 313 ppm, respectively. In the TAS diagram, they plot in the monzodiorite and monzonite fields (fig. 4).

Dikes from both regions belong to the potassic magma series, according to the K2O-versus-Na2O diagram (fig. 4b). In the K2O-versus-SiO2 diagram (fig. 4c), they mainly plot in the shoshonitic and high-K calc-alkaline fields. The dikes have low TiO2 and Fe2O3(tot) contents (fig. 4d). In Fenner-type variation diagrams, they display increasing Fe2O3(tot), CaO, Cr, and Ni concentrations and decreasing SiO2 and Al2O3 with increasing MgO content. No clear correlation exists between TiO2, P2O5, and MgO contents (fig. 5). In primitive mantle–normalized trace-element diagrams (fig. 6a), the dikes show enrichment in Ba, Sr, and other large-ion lithophile elements (LILEs; i.e., Rb, Th, and U) and depletion in high-field-strength elements (HFSEs; i.e., Nb, Ta, Zr, Hf, and Ti). Chondrite-normalized REE patterns (fig. 6b) are characterized by LREE enrichment and heavy-REE depletion ([La/Yb]N = 13.8–46.4), without significant Eu anomalies.

Discussion

Crustal Assimilation and Fractional Crystallization. Results from experimental petrology show that high-Mg# (54–76) rocks are produced by partial melting of mantle peridotite rather than a basaltic progenitor...
Figure 4. Geochemical classification diagrams for intermediate to mafic dikes of the Jiaodong Peninsula: a, (Na$_2$O + K$_2$O) versus SiO$_2$ [Middlemost 1994]; b, K$_2$O versus Na$_2$O [Middlemost 1975]; c, K$_2$O versus SiO$_2$ [Rickwood 1989]; d, TiO$_2$ versus Fe$_2$O$_3$tot. Data for the Jinan-Zouping intrusive rocks are from Ning et al. [2013]. Data for fertile and refractory peridotite melts are from Yang et al. [2004], Cai et al. [2013, 2015], and Ma et al. [2014a, 2014b, 2016].

Figure 5. Fenner variation diagrams for intermediate to mafic dikes of the Jiaodong Peninsula. Red circles are for the Linglong area and blue circles for the Rushan area.
The intermediate to mafic dikes in this study show high Mg# (64–76 for Linglong and 54–73 for Rushan) and high MgO (up to 13.26 wt% for Linglong and 12.73 wt% for Rushan), Cr (239–511 ppm for Linglong and 108–1176 ppm for Rushan), and Ni (84–204 ppm for Linglong and 18.5–313 ppm for Rushan) contents. This suggests that the dikes formed by partial melting of mantle peridotite (Frey and Prinz 1978; Rapp et al. 1999). Compared to those of melts derived from the asthenospheric mantle, the lower TiO₂ and Fe₂O₃(tot) concentrations of the dikes (fig. 4c) suggest a lithospheric mantle source (Ma et al. 2016).

Mantle-derived melts can be contaminated by crustal assimilation or source contamination/metamorphism processes. In cases of crustal assimilation, the magmas should exhibit positive correlations between SiO₂ and ⁸⁷Sr/⁸⁶Sr ratios and negative correlations between SiO₂ and εNd values. As shown in figure 9, initial ⁸⁷Sr/⁸⁶Sr and εNd values of the intermediate to mafic dikes from the Linglong and Rushan regions do not change with the varying SiO₂ contents, suggesting a formation process involving only little crustal assimilation. In addition, variation trends of initial ⁸⁷Sr/⁸⁶Sr ratios and εNd values with silica for the rocks investigated in this study are the same as those in other contemporary mafic rocks in the Jiaodong Peninsula, such as gabbros from the Yinan area, mafic dikes from the Jiaobei terrain, and basic volcanic rocks from the Laiyang basin (Xu et al. 2004b; Liu et al. 2009a; Kuang et al. 2012). This lack of crustal assimilation is consistent with an extensional tectonic regime in eastern China during the Early Cretaceous.

The variable contents of SiO₂, Fe₂O₃, CaO, Al₂O₃, and MgO in the investigated samples indicate that fractionation crystallization played an important role during the magma evolution process. Positive correlations between Cr, Ni, Fe₂O₃, CaO, and MgO and negative correlations between Al₂O₃, SiO₂, and

Figure 6. Primitive mantle–normalized trace-element spidergram (a) and chondrite-normalized rare earth element distribution patterns (b) for intermediate to mafic dikes of the Jiaodong Peninsula. Data for the Jining-Zouping intrusive rocks are from Ning et al. (2013). Data for primitive mantle, chondrite, mid-ocean ridge basalts, and oceanic island basalts (OIB) are from Sun and McDonough (1989).

Figure 7. Initial εNd values versus initial ⁸⁷Sr/⁸⁶Sr ratios. Data sources: Jining-Zouping intrusive rocks: Ning et al. (2013); Cenozoic basalts of the North China Craton (NCC): Wang et al. (2011); Yinan-Fangcheng mafic rocks: Zhang et al. (2002) and Xu et al. (2004b); mafic rocks in the Taihang Mountains: Wang et al. (2006); mafic rocks from the Yangtze Block: Li and Yang (2003); mid-ocean ridge basalts (MORB): Zindler and Hart (1986); marine sediments: Othman et al. (1989); lower crust of the NCC: Jahn et al. (1999); Yangtze upper crust: Gao et al. (1999), Paleozoic kimberlite: Yang et al. (2009; calculated back to 110 Ma). Parameters for the mixing calculation are as follows: mantle: ⁸⁷Sr/⁸⁶Sr = 0.703720, Sr = 20 ppm, εNd = −5, Nd = 1.2 ppm; upper crust: ⁸⁷Sr/⁸⁶Sr = 0.7130, Sr = 350 ppm, εNd = −20, Nd = 26 ppm, lower crust: ⁸⁷Sr/⁸⁶Sr = 0.7100, Sr = 300 ppm, εNd = −35, Nd = 24 ppm.
MgO in the dikes are the results of fractional crystallization of olivine and clinopyroxene (fig. 5f). The lack of correlation between P<sub>2</sub>O<sub>5</sub>, TiO<sub>2</sub>, and MgO contents (fig. 5c, 5h) can be used as a proof of negligible fractional crystallization of apatite and Fe-Ti oxides. Rutile fractionation can also be ruled out because such a process would produce elevated Nb/Ta and Zr/Hf ratios with strongly decreasing Nb and Zr concentrations (Liu et al. 2009a), which are not observed in the investigated samples. As shown in figures 7 and 8, Nd and Pb isotopic compositions of the intermediate to mafic dikes are apparently different from those of the Mesozoic mafic rocks derived from the lithospheric mantle beneath the Yangtze Craton. Previous studies have

![Figure 8](image8.png)

**Figure 8.** Initial 207Pb/204Pb versus 206Pb/204Pb and 208Pb/204Pb versus 206Pb/204Pb for the intermediate to mafic dikes of the Jiaodong Peninsula. Data sources: Jinan-Zouping intrusive rocks: Zhang et al. (2004), Yinan-Fangcheng mafic rocks: Zhang et al. (2002) and Xu et al. (2004b); mafic rocks in Taihang Mountains: Wang et al. (2006), Geochron [4.55 Ga] and Northern Hemisphere reference line (NHRL); Hart (1984), mafic rocks in the North China Craton (NCC): Zhang et al. (2002, 2004), Chen et al. (2004), and Xu et al. (2004b); mafic rocks in the Yangtze Block: Yan et al. (2003, 2005b).

MgO in the dikes are the results of fractional crystallization of olivine and clinopyroxene (fig. 5a–5f). The lack of correlation between P<sub>2</sub>O<sub>5</sub>, TiO<sub>2</sub>, and MgO contents (fig. 5g, 5h) can be used as a proof of negligible fractional crystallization of apatite and Fe-Ti oxides. Rutile fractionation can also be ruled out because such a process would produce elevated Nb/Ta and Zr/Hf ratios with strongly decreasing Nb and Zr concentrations (Liu et al. 2009a), which are not observed in the investigated samples. In the primitive mantle–normalized trace-element patterns (fig. 6a), the dikes show an upper crust–like distribution pattern, with high Pb and K contents and negative Ti, Nb, Ta, and P anomalies. Both the negative correlation of CaO/Al<sub>2</sub>O<sub>3</sub> ratios with decreasing MgO contents (fig. 5j) and the subtly negative Eu anomalies in the chondrite-normalized REE patterns (fig. 6b) indicate that plagioclase was not an important fractionation phase.

**Compositional Characteristics of the Mantle beneath the Jiaodong Peninsula.** The intermediate to mafic dikes in the Linglong and Rushan regions of the Jiaodong Peninsula show geochemical features similar to those of the continental crust–derived melts. These include enrichment in LILEs [Rb, Ba, K, Sr, and Pb] and LREEs, depletion in HFSEs [Nb, Ta, Zr, Hf, and Ti], high 87Sr/86Sr ratios, and negative ε<sub>Nd</sub> values (figs. 6, 7). As crustal contamination was not an important process during emplacement of the dikes, it is more likely that the “crust-like” elemental and isotopic signatures were inherited from the mantle source.

As shown in figures 7 and 8, Nd and Pb isotopic compositions of the intermediate to mafic dikes are apparently different from those of the Mesozoic mafic rocks derived from the lithospheric mantle beneath the Yangtze Craton. Previous studies have

![Figure 9](image9.png)

**Figure 9.** Diagrams of initial 87Sr/86Sr ratio and initial ε<sub>Nd</sub> value versus SiO<sub>2</sub> content for intermediate to mafic dikes of the Jiaodong Peninsula. AFC = assimilation and fractional crystallization; FC = fractional crystallization.
tested that initial $\epsilon_{\text{Nd}}$ values of the Mesozoic Yangtze lithospheric mantle are generally greater than $-10$ and that $^{206}\text{Pb}/^{204}\text{Pb}$ ratios are generally $>18.3$ (Chen et al. 2001; Li and Yang 2003; Wang et al. 2003, 2008; Tang et al. 2014). However, the enriched mantle source identified in this study is characterized by lower initial $\epsilon_{\text{Nd}}$ values $(-10.9$ to $-19.6)$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios $<17.32$ (figs. 7, 8). An explanation for this discrepancy would be that the dikes have probed the lithospheric mantle beneath the NCC.

Until now, it has been stated that the late Mesozoic intermediate to mafic rocks in the Jiaodong Peninsula were derived from enriched mantle sources. How this enriched source formed is still in debate. Several genetic models have been proposed, such as (1) enrichment via multiple metasomatic events during the Late Archean and Mesoproterozoic (Yang et al. 2014), (2) foundering of lower-crustal eclogite during the Late Archean and Mesoproterozoic (Yang et al. 2004), and (3) metasomatism by fluids released from the Paleo-Pacific plate (Niu 2005; Guo et al. 2013a; Ma et al. 2014b; Yang and Santosh 2015), and (4) enrichment related to Mesozoic continental subduction (Zhang et al. 2002; Cai et al. 2013, 2015; Guo et al. 2014). The following observations place constraints on the lithospheric mantle evolution in eastern China. (1) Paleozoic kimberlites from the NCC contain phlogopite megacryst and other metasomatische minerals (e.g., lindsleyite-mathiasite and yimengite-hawthorneite; Zhang 2009 and references therein). This illustrates that the Paleozoic lithospheric mantle beneath the NCC had been metasomatized by small-volume melts before the Paleozoic, but evidence for a thinning of this lithospheric is lacking. (2) The peridotitic xenoliths entrained in the late Mesozoic basaltic rocks indicate that the lithospheric mantle below the NCC was considerably thinned and became heterogeneous during the late Mesozoic. Compared to the Mesozoic lithospheric mantle beneath the NCC, the Paleozone mantle exhibits much higher Nd $[\epsilon_{\text{Nd}}(465 \text{ Ma})$ of $-6.0$ to $1.3$] and Hf $[\epsilon_{\text{Hf}}(465 \text{ Ma})$ of $-6.13$ to $0.52$] values (Yang et al. 2009). If the Mesozoic lithospheric mantle was directly evolved from the Paleozone mantle, then initial $\epsilon_{\text{Nd}}(110 \text{ Ma})$ values of the Mesozoic mantle-derived rocks should lie between $-6.5$ and $-4.9$. The distinct $\epsilon_{\text{Nd}}(110 \text{ Ma})$ values $(-10.9$ to $-19.6)$ of the Early Cretaceous intermediate to mafic dikes from the Linglong and Rushan regions suggest that the enrichment of the lithospheric mantle beneath the eastern NCC must have occurred after the Paleozone (Yang et al. 2009).

Also, initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and initial $\epsilon_{\text{Nd}}$ values of the intermediate to mafic dikes from the Linglong and Rushan regions were not generated by mixing between the Paleozone mantle and the lower continental crust of the NCC (fig. 7). The latter is represented by the Hannuoba, Nushan, and Qianxi granulites, which are characterized by low Rb contents and strong Th and U depletion (Huang et al. 2004; Tang et al. 2009). Trace-element characteristics also support that the lower continental crust of the NCC is not a potential source for generating the enriched geochemical features in the dikes of the Jiaodong Peninsula. On the other hand, the enriched Sr-Nd isotopic compositions of the dikes (Jahn et al. 1999; Zhang et al. 2002; Cai et al. 2013) and the chemical zoning of mantle peridotite xenoliths (Zhang 2005) suggest that the mantle peridotite should be modified by crust-derived silicic melts. Inherited zircons of Neoproterozoic age (Yang et al. 2012b; Cai et al. 2013) found in Mesozoic basaltic rocks and within the intermediate to mafic dikes testify that the silicic melts that enriched the lithospheric mantle were derived from the Yangtze plate. The similar Ti/Ti', Nb/Nb', [Ce/Yb]$_{\text{N}}$, Zr/Nb, Ce/Ba, and Ce/Nb ratios between the dikes and the metasediments and granulites of the Kongling Group also support involvement of the Yangtze lower crust (Zhang et al. 2002), and, taking into account the upper crust-like Nb/U and Ce/Pb ratios of the dikes (fig. 10a, 10b), we suppose that the enriched mantle source beneath the Jiaodong Peninsula was formed by metasomatism of silicic melts or fluids derived from the subducted Yangtze plate.

Moreover, the production of high- and low-Mg adakitic rocks (Liu at al. 2009b; Gu et al. 2013) and asthenosphere-derived magmatic rocks in the Jiaodong Peninsula (Ma et al. 2016) suggests that the lower crust of the NCC has been thickened and delaminated during the Early Cretaceous. Crustal thickening was driven by the subduction of the Yangtze plate (Liu et al. 2008a, 2008b, 2009a, 2009b, 2012, 2013a, 2013b, 2015). The intracontinental compression between the two blocks increased the pressure and temperature of the thickened lower crust and involved the formation of amphibole-bearing eclogites, which have higher density than lithospheric mantle peridotite by 0.2–0.4 g cm$^{-3}$ and thus could be recycled into the mantle (Liu et al. 2009a). Subducted continental crust would be detached from underlying lithosphere mantle if the subduction was sufficiently rapid or if the crust was extremely thick (Zhang and Sun 2002).

In addition, considering the geographic distribution of Mesozoic magmatism in eastern China (Zhou and Li 2000; Wu et al. 2003), the Jiaodong Peninsula is close to either the continental subduction/collision zone of Yangtze plate and NCC or the oceanic subduction zone of the Paleo-Pacific plate (Chen et al. 2004). In accordance with geophysical observations and studies of water content in mantle xenoliths (Xia...
et al. 2013), oblique subduction of the Paleo-Pacific Plate below eastern China occurred during the Early Cretaceous (Zhao and Ohtani 2009). Fluids and/or melts released from the Paleo-Pacific plate could be an important controlling factor for the enrichment of the lithospheric mantle beneath the eastern NCC (Griffin et al. 1998; Niu 2005; Li and Li 2007; Zhao et al. 2007). Ancient oceanic crust from the Paleo-Pacific plate has not been found until now (Zhu et al. 2012a); the significantly low initial $\varepsilon_{Nd}$ values ($219.6$ to $210.9$) of the dikes in the Linglong and Rushan regions cannot be produced through directly partial melting or dehydration of the Paleo-Pacific oceanic slab and/or marine sediments (fig. 7).

As shown in figures 10a and 10b, the Nb/U and Ce/Pb ratios of the intermediate to mafic dikes are similar to those of the average upper continental crust, with their Nb/U ratios varying from 3.0 to 15.7 and their Ce/Pb ratios from 1.5 to 12.5, but are significantly lower than those in mid-ocean ridge and oceanic island basalts (Rudnick and Gao 2003). This brings us to the conclusion that the intermediate to mafic dikes were generated by interactions between recycled upper crust and lithospheric mantle peridotite. The high total alkalis and the high K$_2$O contents of these rocks require sodic and potassic mineral phases, such as phlogopite and/or amphibole, in their source (fig. 4a, 4b; Hou et al. 2010). Rb and Ba are compatible elements in phlogopite (LaTourrette et al. 1995), while Rb, Sr, and Ba are moderately compatible in amphibole (Adam et al. 1993; LaTourrette et al. 1995). In general, melts in equilibrium with phlogopite are expected to have higher Rb/Sr (higher than 0.1) and lower Ba/Rb (lower than 20) ratios than melts in equilibrium with amphibole (Furman and Graham 1999; Tang et al. 2014). As shown in figure 10c, the low Rb/Sr ratios (0.01–0.12) and high Ba/Rb ratios (20.8–64.3) of the dikes from the Linglong and Rushan suggest an amphibole-dominated mantle source in the Jiaodong Peninsula.

The Dy/Yb ratios can be used to estimate the melting depth of magmas, because garnet lherzolite–derived melts generally have high Dy/Yb ratios (>2.5), whereas melts derived from the spinel lherzolite generally have low Dy/Yb ratios (<1.5; Duggen et al. 2005; Tang et al. 2014; Ma et al. 2014a). Intermediate to mafic dikes from the Linglong and Rushan regions have moderate Dy/Yb ratios of 1.91–2.72.
In the Dy/Yb-versus-K/Yb × 10² diagram, they plot between the partial melting curves of garnet-facies and spinel-facies amphibole lherzolite, indicating that melting took place in the spinel-garnet transition zone at a 75–85-km depth (fig. 10d; McKenzie and O’Nions 1991; Tang et al. 2014; Ma et al. 2014a).

**Petrogenesis and Tectonic Implications.** Mafic rocks from other localities can put additional constraints on the NCC subcraton mantle. The Jinan-Zouping region is located at the southeastern edge of the NCC, while the Taihang Mountains belong to the central part of the NCC (fig. 1a). Mafic rocks from the Jinan-Zouping region exhibit the lowest initial ⁸⁷Sr/⁸⁶Sr ratios [0.7043–0.7062] and initial εNd values (−19.0 to −7.4; Ning et al. 2013), as well as low ²⁰⁶Pb/²⁰⁴Pb (16.560 to 16.837), ²⁰⁷Pb/²⁰⁴Pb (15.216 to 15.283), and ²⁰⁸Pb/²⁰⁴Pb (36.290–36.724) ratios (Zhang et al. 2004). Enrichment of LILEs and a fractionated REE pattern ([La/Yb]N of 3.32–30.61), with notable negative Nb, Ta, and Ti anomalies, as well as the depletion of Th and U relative to La ([Th/La]N of 0.15–1.68, mostly <1; Ning et al. 2013), of these mafic rocks suggest the presence of an enriched mantle source below the central NCC. Similar Sr-Nd-Pb isotopes of the mafic rocks from Jinan-Zouping and the Taihang Mountains (fig. 1a) confirm that they originate from a typical NCC mantle source. On the other hand, the Yinan-Fangcheng region, located southeast of the Jinan-Zouping region, is also a part of the southeastern edge of the NCC but is adjacent to the Dabiesulu orogenic belt (fig. 1a). As shown in figures 7 and 8, Sr-Nd-Pb isotopes of the mafic igneous rocks in the Yinan-Fangcheng region are different from those of the Jinan-Zouping region and the Taihang Mountains but similar to those from the Jiaodong Peninsula, with their initial ⁸⁷Sr/⁸⁶Sr ratios varying from 0.7096 to 0.7117, initial εNd values from −15.4 to −11.1, initial ²⁰⁶Pb/²⁰⁴Pb ratios from 17.181 to 17.649, ²⁰⁷Pb/²⁰⁴Pb ratios from 15.477 to 15.591, and ²⁰⁸Pb/²⁰⁴Pb ratios from 37.536 to 38.472 (Yang et al. 2012a).

When the data from the intermediate to mafic dikes of the Jiaodong Peninsula are included, it appears that there were two types of enriched mantle domains beneath the Shandong Province during the Early Cretaceous, one closer to EM2-type composition in the eastern part and the other more akin to EM1-type composition in the western part. These characteristics of the mantle sources are also consistent with a highly heterogeneous late Mesozoic lithospheric mantle beneath the NCC (Zhang et al. 2004). The spatial variations in whole-rock Sr-Nd-Pb isotopic compositions of Early Cretaceous can be explained by the northwestward-subduction model of the South China Block beneath the North China Block during the Triassic (e.g., D.-B. Yang et al. 2012a; Q.-L. Yang et al. 2012c). In addition, similar zircon Hf modal ages in mafic dikes and metamorphic rocks of the Sulu belt (Cai et al. 2015) also suggest that the subducted continental crust of the Yangtze Craton played a role as a source component of the magma from which the dikes formed. We suggest that heterogeneities within the lithospheric mantle sources are related to the northward subduction of the Yangtze plate during the Triassic. In such a scenario, the EM2-like mantle domain would be produced by interaction between subducted continental crust and mantle peridotite beneath the southeastern margin of the NCC (Zhang et al. 2002). Because the central NCC (e.g., the Jinan-Zouping region and the Taihang Mountains) is located more than 200 km from the Dabiesulu orogenic belt, the EM1-like mantle type beneath the central NCC remained unaffected by the Triassic subduction.

Nevertheless, dike emplacement within the Jiaodong Peninsula was not triggered by the collapse of the Dabiesulu orogen during the Triassic. Instead, abundant magmatic activity took place during the Early Cretaceous, about 100 My later, after the time of the continental subduction/collision, and the Cretaceous magmatic rocks are widely distributed throughout eastern China.

**Figure 11.** Age distribution pattern of Mesozoic mantle-derived rocks in the Shandong Province. Data for eastern Shandong are from Guo et al. (2004), Liu et al. (2004b, 2008a, 2009a), Yang et al. (2004, 2005), Yan et al. (2005a), Tan et al. (2008), Zhang et al. (2008), Tang et al. (2009, 2014), Kuang et al. (2012), Cai et al. (2013, 2015), Ma et al. (2014a, 2014b), and this study. Data for western Shandong are from Zhang et al. (2002), Liu et al. (2004b, 2008a), Xu et al. (2004a, 2004b), C.-H. Yang et al. (2006), Huang et al. (2012), Lan et al. (2012), Q.-L. Yang et al. (2012c), Guo et al. (2013a), and Ning et al. (2013). A color version of this figure is available online.
The statistical distribution of zircon ages from mantle-derived igneous rocks (fig. 11) illustrates that the Early Cretaceous magmatism migrated from the west to the east in Shandong Province. The mantle-derived igneous rocks from both the western and eastern parts of Shandong Province can be divided into two age groups: 185–177 Ma (asthenosphere derived) and 144–101 Ma (lithosphere derived) for the western part (Jinan-Zouping and Yinan-Fangcheng regions) and 134–102 Ma (lithosphere derived) and 95–73 Ma (asthenosphere derived) for the eastern part (Jiaodong Peninsula; Zhang et al. 2002; Xu et al. 2004b; Huang et al. 2012; Ning et al. 2013; Guo et al. 2013a; Liu et al. 2015). This age progression is consistent with the rollback of the subducted Paleo-Pacific plate during the Early Cretaceous (e.g., Yang et al. 2014b, 2014c, 2017). Although ancient crust of the Paleo-Pacific plate has not been found until now (Zhu et al. 2012a) and the direct material contribution from the Paleo-Pacific plate (Zhang 2005; Zhu et al. 2012a) has not been verified yet, the rollback of the Paleo-Pacific plate could also have caused the decompression of the lithospheric mantle and upwelling of asthenospheric mantle that led to the partial melting of the previously enriched lithospheric mantle.

Figure 12 shows a possible tectonic model for the Triassic and Early Cretaceous evolution of Shandong Province. Crust from the Yangtze Craton was subducted toward depths of c. 150–200 km (Ye et al. 2000; Zhang and Sun 2002) and rapidly moved upward after a breakoff of the subducted Yangtze Block (Davies and von Blanckenburg 1995). Dehydration and anatexis of the UHP crustal rocks produced a variety of melts and fluids enriched in LILEs and LREEs and depleted in HFSEs (Zheng and Herrmann 2014; Xiao et al. 2015). These melts and fluids migrated into the overlying mantle wedge of the NCC, causing metasomatism of the subcontinental lithospheric mantle peridotite. This metasomatized subcontinental mantle is regarded as a potential source for the Early Cretaceous mafic magmatism.

In the Middle Jurassic, the Paleo-Pacific plate began to subduct beneath the Eurasian continent, and eastern China was transformed into an active continental margin (fig. 12b). Apart from I-type granitoids, numerous A-type granites (Zhao et al. 1998; Wang et al. 2001) formed during the Early Cretaceous, indicating that an extensional tectonic regime and large-scale mineralization formed during this period in eastern China (Guo et al. 2013b; Sun

Figure 12. Cartoon sketch of tectonic model for better understanding the formation process of the Early Cretaceous intermediate to mafic dikes in Shandong Province, showing major processes of continental subduction/collision, metasomatism, mafic and felsic magma formation, magmatic underplating, heterogeneous lithospheric thinning, delamination, and oceanic plate subduction (modified after Guo et al. 2013b and Yang et al. 2014a). UHP = ultrahigh pressure. Processes in b: 1, melting of basement rocks in the lower and middle crust; 2, partial melting of lithospheric mantle; 3, heterogeneous lithospheric thinning; 4, asthenospheric upwelling; 5, delaminated eclogitic crust sinking into mantle transition zone; 6, subducted Paleo-Pacific plate stagnant at the mantle transition zone.
et al. 2013; Goldfarb and Santosh 2014; de Boorder 2015; Santosh and Pirajno 2015; Yang and Santosh 2015). In addition, a series of NE- to NNE-striking faults, fault-controlled graben basins (Zhu et al. 2008), and metamorphic core complexes (Charles et al. 2011, 2013) formed since the Jurassic. All these geological features suggest that the subduction of the Paleo-Pacific plate had a fundamental influence on Early Cretaceous magmatism in eastern China.

With the onset of rollback, the tectonic setting in eastern China changed from compression to extension. Consequently, decompression partial melting is the most possible formation mechanism for the Early Cretaceous dikes in Shandong Province. Along the Tan-Lu fault, the lithospheric mantle was gradually thinned. This process was probably accompanied by delamination of the eclogitic lower crust, resulting in a heterogeneous lithospheric mantle composition and a complete destruction of the old lithosphere regime. Water from the subduction of the Paleo-Pacific plate would reduce the melting point of the lithospheric mantle, which had been metasomatized by the subducted continental crust of the Yangtze Craton during the Triassic. This Mesozoic lithosphere enriched in Sr-Nd-Pb isotopic signatures was the source for the Early Cretaceous dikes.

Conclusions

New zircon U-Pb ages and geochemical and Sr-Nd-Pb isotopic data on intermediate to mafic dikes in the Linglong and Rushan regions lead to the following conclusions. (1) Zircon dating results show that the dikes in the Jiaodong Peninsula were formed during the Early Cretaceous, between 118 and 108 Ma in the Rushan region and between 124 and 121 Ma in the Linglong region. (2) The intermediate to mafic dikes display high Mg# and high Cr and Ni contents with enrichment in LREEs, LILs, and Sr isotopic composition and depletion in HFSEs, implying the involvement of an enriched mantle source component. The low Rb/Sr, high Ba/Rb, and moderate Dy/Yb ratios suggest an amphibole-bearing mantle source within the spinel-garnet transition zone. (3) The “crust-like” geochemical and Sr-Nd-Pb isotopic data imply that the enriched mantle beneath the Jiaodong Peninsula was metasomatically modified by silicic melts derived from the subducted Yangtze continental crust during the Triassic. (4) The dikes in the Jiaodong Peninsula were most likely formed by partial melting in a decompression setting caused by rollback of the Paleo-Pacific plate.

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