Subduction-related metasomatism in the thinning lithosphere: Evidence from a composite dunite-orthopyroxenite xenolith entrained in Mesozoic Laiwu high-Mg diorite, North China Craton

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[1] The North China Craton (NCC) lost its Archean keels in the Phanerozoic. Prevalent and intensive magmatism, mineralization, and development of extensional basins in the late Mesozoic NCC imply that the late Mesozoic could be the key stage for this transformation. Ultramafic xenoliths in the Early Cretaceous high-Mg diorites of Shandong province might provide key information about the transformation of subcontinental lithospheric mantle (SCLM) beneath the NCC. Here we present a unique composite dunite-orthopyroxenite xenolith from Tietonggou, one of the high-Mg diorite-dominated plutons in Laiwu, Shandong province. The petrography and mineral chemistry of the xenolith suggest complicated metasomatic processes, which occurred before its entrainment in the host magma. Early stage metasomatism includes the growth of intergranular phlogopite and clinopyroxene and the development of a phlogopite- and amphibole-bearing clinopyroxenite veinlet. Late-stage metasomatism (termed Si (Na) metasomatism) is characterized by the growth of secondary orthopyroxene, Na-rich plagioclase and amphibole with resorption of olivine and clinopyroxene, and the decomposition of phlogopite. The xenolith has exceptionally high concentrations of Na₂O and Al₂O₃ and shows enrichments in Cs, Rb, Th, U, K, and the light rare earth elements. It also shows positive Pb and Sr anomalies and negative Nb, Ta, P, and Ti anomalies in a primitive mantle normalized spider gram. The geochemistry, as well as the elevated δ¹⁸O, suggests that this Si (Na) metasomatism is associated with subduction. The secondary orthopyroxene in the orthopyroxenite portion of the xenolith has exceptionally low Mg# values, which may be the result of reaction between silica-rich melts and olivine with high melt:rock ratios. Mg-Fe disequilibrium of the minerals in the orthopyroxenite indicates that Si (Na) metasomatism may have been introduced shortly before entrainment of the xenolith in the host magma. Correlation of the Sr-Nd-Pb isotopic compositions of ultramafic xenoliths, high-Mg diorites, and adakitic granites of the Tietonggou indicates there may be a genetic relationship between these rocks. Thus we propose that the SCLM beneath Shandong may have been metasomatized by a slab-derived melt. Since Si (Na) metasomatism occurred at the key stage of lithospheric thinning, oceanic subduction might have been involved in the thinning process.

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Keywords: mantle xenolith; mantle metasomatism; lithosphere thinning; subduction; North China Craton.

Index Terms: 1025 Geochemistry: Composition of the mantle; 3621 Mineralogy and Petrology: Mantle processes (1038); 3613 Mineralogy and Petrology: Subduction zone processes (1031, 3060, 8170, 8413).
1. Introduction

[2] The stability and fate of subcontinental lithospheric mantle (SCLM) is an important unresolved issue. The North China Craton (NCC) is one of the oldest Archean cratons on the earth [Jahn et al., 1987; Liu et al., 1992], and is surrounded by the NE China fold belts, the Qinlin-Dabie-Sulu orogenic belts, and the Yangtze craton (Figure 1). Mantle xenoliths from the Paleozoic kimberlites of Mengyin and Fuxian suggest that the SCLM beneath the NCC is thick (180–200 km), cold and refractory, like other Archean cratons [Menzies et al., 1993; Griffin et al., 1998]. However, mantle xenoliths from the Cenozoic basalts suggest a thin (<80 km), hot and fertile SCLM in the eastern NCC [Fan et al., 2000]. Thus the SCLM beneath the eastern NCC suffered a massive transformation (or thinning) in the Phanerozoic. Recent evidence from Os isotopes of peridotite xenoliths also supports such a conclusion [Gao et al., 2002; Wu et al., 2003]. Although the direct mechanism and geodynamics remain controversial, the prevalent and intensive late Mesozoic magmatism, mineralization, and the development of extensional basins in the region imply that the late Mesozoic could be a key stage for this major lithospheric transformation [Menzies and Xu, 1998; Xu, 2001; Zhang et al., 2002, 2003; Zhou et al., 2002; Yang et al., 2003; Zhai et al., 2004; Xu et al., 2004b, 2004c; Xu et al., 2004]. The discovery of ultramafic xenoliths in the Cretaceous high-Mg diorites and basalts of the eastern NCC in recent years, such as Laiwu (125–131 Ma), Zibo (112–129 Ma), Fangcheng (125 Ma), Fuxin (100 Ma), and Jiaozhou (74 Ma), not only provide direct SCLM samples of the late Mesozoic [Xu et al., 1993; Zheng et al., 1999; Zhang et al., 2002; Xu et al., 2003a; Yan et al., 2003; Chen and Zhou, 2004], but also more crucial information about the thinning process.

[3] Shandong province is located in the central part of the eastern NCC, and is divided into two parts, west Shandong (Luxi area) and east Shandong (Jiaodong area), by the giant Tan-Lu wrench fault (Figure 1). Early Cretaceous igneous rocks are ubiquitous in Shandong province, and include gabbro-dominated plutons in the north of west Shandong [Dong, 1987; Guo et al., 2001], high-Mg diorite-dominated plutons in west Shandong [Dong, 1987; Chen, 2001; Xu et al., 2004], granite-dominated plutons in east Shandong [Yang and Zhou, 2001], medium-mafic volcanics or lamprophyres distributed throughout the whole province [Qiu et al., 2002; Ying, 2002; Guo et al., 2003; Yang et al., 2004], and a few carbonatites in Laiwu and Zibo [Ying, 2002; Ying et al., 2004]. Laiwu basin is situated in the center of west Shandong, near the Tan-Lu fault (Figure 1). There are four high-Mg diorite-dominated plutons in Laiwu, including Kuangshan, Jiaoyu, Jinniushan, and Tietonggou [Dong, 1987; Chen, 2001]. Abundant ultramafic xenoliths had been found in the Tietonggou intrusion [Xu et al., 1993; Chen, 2001; Chen and Zhou, 2004]. K-Ar and Ar-Ar dating of the intrusion gives an age of 125–133 Ma [Chen, 2001; Xu et al., 2004b], which is consistent with the SHRIMP U-Pb age (130.2 Ma) of the Jiaoyu intrusion [Xu et al., 2004]. The lithology, mineral chemistry, equilibrium temperature (690–790°C), and metasomatic characteristics of the ultramafic xenoliths indicate that they might be derived from the shallow lithosphere (the crust-mantle transitional zone) and were metasomatized by hydrous silicarich melts [Chen and Zhou, 2004]. Similar Sr-Nd isotopic compositions indicate that there may be genetic links between these xenoliths and their host rocks [Chen and Zhou, 2004]. Here we report the petrology, geochemistry and Sr-Nd-Pb-O isotopic composition of a unique composite xenolith (dunite + orthopyroxenite), which presents more detailed metasomatic information than previously reported xenoliths. Furthermore, this paper provides evidence on the timing of the metasomatism and the source characteristics of the metasomatic liquids, which may help to understand the thinning process of the SCLM of the NCC.

2. Petrography
pluton. We prepared a large thin section to view the whole structure of the specimen (Figure 2), and two small thin sections for mineral analysis (Figure 3). The specimen is a composite xenolith, composed mainly of phlogopite-rich orthopyroxenite, and several minor dunite cores (Figure 2). The dunites have heterogeneous abundances of spinel. Some dunite cores are enriched in spinel, up to 30%, such as dunite A in the left thin section of Figure 3, whereas others have low spinel contents, less than 2%, such as dunite B in the right thin section of Figure 3. All dunites exhibit porphyroclastic texture and recrystallization textures. Porphyroblasts of olivine are commonly kinked, while fine-grained recrystallized olivines are free of kink bands. The boundary between the host diorite and the orthopyroxenite portion of the xenolith is sharp (Figures 2 and 4a). A hornblende selvage is in contact with a dunite core in the xenolith (Figures 2 and 4b). The boundaries between dunite and orthopyroxenite are sharp and curved (Figures 2, 3, and 4c), and the composite xenolith resembles a conglomerate with dunite pebbles (Figure 2).

Dunite A is characterized by a high abundance of spinel (Figure 3). The spinel is usually euhedral or subhedral in shape and 50–400 μm in size. One composite veinlet found in dunite A is composed primarily of orthopyroxenite with minor clinopyroxenite (Figure 5a). The clinopyroxenite occurs...
only at the center of the veinlet, which has a turbid appearance due to exsolution of the minerals (Figure 5a). The clinopyroxenite is composed of clinopyroxene, phlogopite, and amphibole (Figure 5b), whereas the orthopyroxenite consists only of orthopyroxene with a clean appearance.

[6] Dunite B has a low abundance of spinel (Figure 3). The spinel is anhedral and small (less than 50 μm). Anhedral phlogopites are disseminated unevenly between olivines (Figure 6a). A back-scattered electron (BSE) image shows that the minerals located interstitial to the olivines include not only phlogopite, but also clinopyroxene, orthopyroxene, plagioclase, and amphibole (Figure 6b). Clinopyroxene and phlogopite are partly replaced by orthopyroxene, plagioclase and amphibole, but the relationship between clinopyroxene and phlogopite is unclear. Orthopyroxene is also situated along the boundaries between olivine grains (top left of Figure 6b) and the contacts between orthopyroxene and olivine are straight and sharp.

[7] The orthopyroxenite has complicated mineral compositions and metasomatic textures (Figure 7). Orthopyroxenes and phlogopites are the main phases, with minor olivine, plagioclase and spinel, calcite, zircon, rutile, and apatite as accessory minerals. Porphyroblasts of orthopyroxene have turbid appearances due to the presence of numerous inclusions, such as resorbed olivine, spinel, phlogopite as well as fluid inclusions (Figure 7a). Phlogopite is commonly ragged and decomposes into anhydral orthopyroxene and plagioclase.
Olivines exist as resorbed inclusions in orthopyroxene and phlogopite (Figures 7a and 7b). Fine-grained anhedral spinels (most less than 20 μm size) occur throughout. Some spinels exist as inclusions in orthopyroxene and phlogopite, while others constitute as pseudomorphs of euhedral spinel.

3. Mineral Chemistry

Mineral chemistry was analyzed with a JEOL Superprobe JXA 8100 electron-probe microanalyzer (EPMA) at the School of Earth and Space Sciences, Peking University and a JEOL JXA 8800M EPMA at the Department of Earth Sciences, Nanjing University, using an accelerating voltage of 15 kV, beam currents of $1 \times 10^{-8}$ A and $2 \times 10^{-8}$ A respectively, and 1 μm beam size. The counting times for Ni, Mn, and Ca in olivine are longer than that for other elements. Selected microprobe analyses of dunite A, dunite B, and orthopyroxenite are listed in Tables 1–3, respectively.

3.1. Olivine

Olivine in dunite A is chemically heterogeneous. The olivine in spinel-rich portion has the highest Mg# value ($\text{Mg#} = \frac{\text{Mg}}{(\text{Mg} + \text{Fe}^{2+})} \times 100$) of 94.4, while olivine in the spinel-depleted area has a lower Mg# value of 92.3. Olivine in dunite B has a lower Mg# value of 88.2 and olivine in orthopyroxenite has the lowest Mg# values of 85.5–86.6. The range of Mg# values in primitive olivines from other peridotite xenoliths in Tietonggou is from 87 to 93.

3.2. Spinel

Spinel in dunite A is characterized by high Cr$_2$O$_3$ (56 wt%), MgO (10.9 wt%), and low total

Figure 5. Metasomatic veinlet in dunite A of xenolith LW0006. (a) The veinlet is a composite composed of phlogopite- and amphibole-bearing clinopyroxenite in the center and orthopyroxenite along the two sides. Exsolution texture is observed in the amphiboles associated with the clinopyroxenite. Crossed-polarized light. (b) Back-scattered electron (BSE) image of the clinopyroxenite portion of the composite veinlet. Abbreviations: opx-ite, orthopyroxenite; cpx-ite; clinopyroxenite; ol, olivine; cpx, clinopyroxene; phl, phlogopite; amp, amphibole.

Figure 6. Metasomatic textures in dunite B of xenolith LW0006. (a) Yellow phlogopites, as well as other metasomatic minerals, are disseminated in dunite. Plane-polarized light. (b) BSE image shows five minerals located interstitial to the olivines, including clinopyroxene (cpx), phlogopite (phl), orthopyroxene (opx), Na-rich plagioclase (pl), and Na-rich amphibole (amp). Clinopyroxene are separated by phlogopite, and both clinopyroxene and phlogopite are partly replaced by orthopyroxene, plagioclase, and amphibole. Orthopyroxene also can be seen at the triple junction and along the boundaries of the olivines.
FeO (20.9 wt%), Al₂O₃ (9.3 wt%), TiO₂ (0.28 wt%) concentrations, with high Mg# (54.9) and Cr# (Cr# = Cr/(Cr + Al + Fe³⁺) × 100) (80.3). Spinel in dunite B has lower concentrations of Cr₂O₃ (40 wt%), MgO (8.1 wt%), and higher concentrations of total FeO (30.5 wt%), Al₂O₃ (19.6 wt%), and TiO₂ (0.32 wt%) contents, with lower Mg# (34.8) and Cr# (60.6). The Mg# and Cr# of spinel in the orthopyroxenite have broad ranges of 34.8–38 and 46–70, respectively. Spinel rims usually has lower Mg# and Cr# values and higher TiO₂ concentrations than the spinel cores (Table 3). Such chemical heterogeneity is common in spinels from Tietonggou xenoliths.

3.3. Orthopyroxene

Orthopyroxene in the xenolith has low Al₂O₃ contents (0.8–2.6 wt%), which is consistent with orthopyroxene from other Tietonggou xenoliths, but is different from orthopyroxene in mantle xenoliths entrained by Cenozoic basalts of the NCC (Figure 8). The orthopyroxene in this xenolith can be distinguished from the primary orthopyroxene of Tietonggou peridotite xenoliths by the broad range of Cr₂O₃ (0–0.95 wt%) and CaO concentrations (0.31–0.89) (Figure 8). Orthopyroxene in the veinlet of dunite A has the highest Mg# (91.8–92.6) and Cr₂O₃ concentrations (0.42–0.95 wt%), and the lowest concentrations of Al₂O₃ (0.79–1.38 wt%) in the composite xenolith. Orthopyroxene in dunite B has an intermediate Mg# (88.1–88.7), and intermediate concentrations of Cr₂O₃ (0.15–0.60 wt%) and Al₂O₃ (1.20–1.68 wt%). Orthopyroxene in the orthopyroxenite has a broad compositional range with the lowest Mg# (85.2–87.9) and Cr₂O₃ concentrations (0–0.31 wt%), and the highest Al₂O₃ concentrations (1.0–2.6 wt%) in the composite xenolith.

3.4. Phlogopite

Phlogopite in the clinopyroxenite portion of the composite veinlet of dunite A is characterized with high Mg# value (95.7–95.9), high CaO (0.24–1.38 wt%), and low TiO₂ content (0.04–0.08 wt%). Disseminated phlogopite in dunite B is characterized with low Mg# value (89.2–90.2), low CaO (0–0.20 wt%), and high TiO₂ content (2.3–3.4 wt%). Ragged phlogopite in the orthopyroxenite part is characterized with broad composition and low Mg# value (89.1–92.0), low CaO (0–0.13 wt%), and high TiO₂ contents (1.1–2.2 wt%).

3.5. Clinopyroxene

Clinopyroxene in the clinopyroxenite portion of the composite veinlet of dunite A is Ca-rich diopside with a high Mg# (95.2). The clinopyroxene contains no Cr₂O₃, which is different from the
primitive clinopyroxene (Cr-rich diopside with 0.63–1.22 wt% Cr$_2$O$_3$) of other Tietonggou peridotites. Disseminated clinopyroxene in dunite B has lower Mg# (89.6–91.0), high Cr$_2$O$_3$ concentrations (0.40–0.84).

### 3.6. Amphibole

[14] Amphibole in the clinopyroxenite of the composite veinlet of dunite A exhibits high Mg# (95.2), high SiO$_2$ (52.2 wt%), and CaO (20.5 wt%), and low Al$_2$O$_3$ (2.6 wt%), Na$_2$O (0.36 wt%), TiO$_2$ (0.07 wt%) and Cr$_2$O$_3$ (<0.01 wt%) concentrations. Amphibole in dunite B exhibits low Mg# value (86.3), low concentrations of SiO$_2$ (44.3 wt%) and CaO (13.1 wt%), and high concentrations of Al$_2$O$_3$ (12.1 wt%), Na$_2$O (2.84 wt%), TiO$_2$ (1.81 wt%), and Cr$_2$O$_3$ (1.1 wt%), which is consistent with Na-rich amphiboles in orthopyroxenite veinlets observed in other Tietonggou xenoliths.

### 3.7. Plagioclase

[15] Plagioclase in dunite B and in the orthopyroxenite are both enriched in Na$_2$O (Na$_2$O = 2.7–7.9 wt%) and show broad compositional ranges (An$_{32-75}$Ab$_{25-70}$). They have depleted K contents (K$_2$O < 0.06 wt%), which differ from plagioclase in the host diorite (K$_2$O = 0.13–0.45 wt%).

### 4. Analytical Procedures and Results

The specimen was first cut into several pieces. One piece selected from the inner part of the dunite A was cut into several pieces, and one piece selected from the inner part of the dunite B was cut into several pieces.
Xenolith was mainly composed of orthopyroxenite (>95 vol.%) with minor dunite. This portion was broken into small fragments about 1/25 mm size, which were rinsed with distilled water and dried in an oven. The dried fragments were then milled into 200 mesh for chemical analysis. Major elements were measured on glass fusion discs by RIX-2100 X-ray fluorescence at the Key Laboratory for Continental Dynamics, Northwest University (Xi’an, China). The precision (relative 2σ error) for major elements is estimated to be <1%. Results (in wt%) are shown in Table 4.

Analysis of trace elements and isotopic compositions was done at the Institute of Geology and Geophysics, Chinese Academy of Sciences. Chemical processing of the sample was carried out in an ultra-clean laboratory. Trace elements in the xenolith were analyzed by a Finnigan MAT ICP-MS following the procedures outlined by Jin and Zhu [2000], together with three standards and a blank. On the basis of the repeated analyses of standards and parallel samples, the 2σ error of the analyses is estimated to be <20% for Co, Cr, Ga, Ba, Zr, Ta, Pb, and <10% for Li, Sc, V, Ni, Cu, Sr, Y, Nb, Cs, Hf, Th, U, Tm, Lu and <5% for the rare earth elements (REE) except Tm and Lu. Results (in ppm) are shown in Table 4.

Sr-Nd-Pb isotopic analyses were carried out using a VG354 mass spectrometer according to the procedures of Yang and Zhou [2001]. During the chemical processing of the sample was carried out in an ultra-clean laboratory. Trace elements in the xenolith were analyzed by a Finnigan MAT ICP-MS following the procedures outlined by Jin and Zhu [2000], together with three standards and a blank. On the basis of the repeated analyses of standards and parallel samples, the 2σ error of the analyses is estimated to be <20% for Co, Cr, Ga, Ba, Zr, Ta, Pb, and <10% for Li, Sc, V, Ni, Cu, Sr, Y, Nb, Cs, Hf, Th, U, Tm, Lu and <5% for the rare earth elements (REE) except Tm and Lu. Results (in ppm) are shown in Table 4.

Figure 8. Chemical compositions of orthopyroxene in xenolith LW0006. A, dunite A; B, dunite B; O, orthopyroxenite. Orthopyroxenes in Tietonggou xenoliths have lower Al2O3 concentrations than those in Cenozoic peridotite xenoliths [Rudnick et al., 2004]. Cr2O3 and CaO concentrations in secondary orthopyroxenes have broader ranges than primitive orthopyroxenes in Tietonggou xenoliths. In xenolith LW0006 the Cr2O3 contents of secondary orthopyroxenes in dunite A are higher than those of dunite B and the orthopyroxenite.

Table 3. Representative EMP Analyses of Minerals in the Orthopyroxenite Part of Xenolith LW0006a

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a² is a fine-grained spinel. 3 and 4 are the core and the rim of a relatively coarse spinel, respectively.
611.0x789.0

period in which the analyses were carried out, the measured $^{87}\text{Sr}/^{86}\text{Sr}$ value of NBS607 was 1.20055 ± 2, repeat analyses of the liquid standard La Jolla gave $^{143}\text{Nd}/^{144}\text{Nd}$ values of 0.511855 ± 9, the measured $^{143}\text{Nd}/^{144}\text{Nd}$ value of BCR1 was 0.512651 (9) and repeat analyses of NBS981 yielded $^{204}\text{Pb}/^{206}\text{Pb} = 0.05900 ± 8$, $^{207}\text{Pb}/^{206}\text{Pb} = 0.91439 ± 17$ and $^{208}\text{Pb}/^{206}\text{Pb} = 2.16441 ± 97$, respectively. The measured Sr-Nd-Pb isotopic ratios of this sample (>95 vol.% orthopyroxenite and <5 vol.% dunite) are listed in Table 5.

For analyses of $^{18}\text{O}$, the sample was first reacted with BrF$_5$, after which the liberated oxygen was converted to CO$_2$ by reaction with graphite at 500°C, the CO$_2$ produced was absorbed by liquid nitrogen and was then analyzed by a Finnigan MAT Delta S mass spectrometer. The standard NBS-28 used in this study gave a $^{18}\text{O}$$_{\text{V-SMOW}}$ value of 9.65 ± 0.15 %.

5. Geochemistry and Isotopic Composition

Table 4. Major Elements and Trace Elements of Xenolith LW0006

<table>
<thead>
<tr>
<th>Element</th>
<th>SiO$_2$</th>
<th>TiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3$</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na$_2$O</th>
<th>K$_2$O</th>
<th>P$_2$O$_5$</th>
<th>LOI</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>9.79</td>
<td>4.06</td>
<td>49.6</td>
<td>2711</td>
<td>104</td>
<td>1336</td>
<td>16.3</td>
<td>6.22</td>
<td>19.6</td>
<td>174</td>
<td>4.18</td>
<td>49.3</td>
</tr>
<tr>
<td>Nb</td>
<td>2.19</td>
<td>1.39</td>
<td>114</td>
<td>1.22</td>
<td>0.18</td>
<td>89.2</td>
<td>2.68</td>
<td>0.84</td>
<td>9.41</td>
<td>16.5</td>
<td>1.83</td>
<td>6.87</td>
</tr>
<tr>
<td>Sm</td>
<td>1.24</td>
<td>0.399</td>
<td>1.19</td>
<td>0.16</td>
<td>0.88</td>
<td>0.17</td>
<td>0.48</td>
<td>0.08</td>
<td>0.49</td>
<td>0.07</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Major element units are oxide wt%, and trace element units are ppm.

Table 5. Sr-Nd-Pb Isotopic Composition of Xenolith LW0006

<table>
<thead>
<tr>
<th>Rb</th>
<th>Sr</th>
<th>$^{87}\text{Rb}/^{86}\text{Sr}$</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$ (2σ)</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}_i$</th>
<th>$\varepsilon_{\text{Sr(T) (T)}}$</th>
<th>$T_{\text{DM}}$</th>
<th>$f_{\text{Sm/Nd}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.35 ppm</td>
<td>176.4 ppm</td>
<td>0.4642</td>
<td>0.706954(29)</td>
<td>0.706129</td>
<td>25.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.07 ppm</td>
<td>5.78 ppm</td>
<td>0.1120</td>
<td>0.512213(8)</td>
<td>0.512121</td>
<td>$\Delta$7/4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^{206}\text{Pb}/^{204}\text{Pb}$ | $^{207}\text{Pb}/^{204}\text{Pb}$ | $^{208}\text{Pb}/^{204}\text{Pb}$ | $^{206}\text{Pb}/^{204}\text{Pb}_i$ | $^{207}\text{Pb}/^{204}\text{Pb}_i$ | $^{208}\text{Pb}/^{204}\text{Pb}_i$ |
| 17.164 | 15.410 | 37.534 | 17.151 | 15.409 | 37.521 | 5.9 | 116.1 |

*Initial values were calculated at 125 Ma.
On a $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ diagram, the range of Tietonggou xenoliths is distinct from that of Cenozoic basalts and their entrained xenoliths in Shandong province (Figure 11a), but is similar to that of their host rocks (Figure 11b). The lead isotopic composition of this sample, $^{206}\text{Pb}/^{204}\text{Pb} = 17.164$, is less radiogenic than the Cenozoic basalts in Shandong province ($^{206}\text{Pb}/^{204}\text{Pb} = 17.60/C0_{18.46}$ [Peng et al., 1986]), but more radiogenic than Ji’nan gabbros ($^{206}\text{Pb}/^{204}\text{Pb} = 16.62/C0_{16.94}$ [Zhang et al., 2004]).

6. Discussion

6.1. Xenolith LW0006: An Extreme Example of Ultramafic Xenoliths Entrained in the Early Cretaceous Diorite of NCC

[24] The metasomatism observed in xenolith LW0006, has also been found in peridotite xenoliths of Tietonggou [Chen and Zhou, 2004], e.g., (1) disseminated phlogopite and clinopyroxene which are partially replaced by late-stage orthopyroxene, Na-rich plagioclase, and Na-rich amphibole, (2) phlogopite- and amphibole-bearing clinopyroxene veinlets, (3) Na-rich amphibole- and plagioclase-bearing orthopyroxene veinlets. Orthopyroxene veinlets have been found in most

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**Figure 9.** Major element composition of xenolith LW0006. Data for peridotite xenoliths from Cenozoic basalts of Shandong province are from Rudnick et al. [2004]. Data of other ultramafic xenoliths of Tietonggou are from Chen and Zhou [2004] and Xu et al. [2004a]. Archon is the average SCLM of the Archean craton [Griffin et al., 2003]. PM is primitive mantle from McDonough and Sun [1995].
peridotite xenoliths from Tietonggou. Several orthopyroxenite veinlets can be observed in those large peridotite xenoliths. The mineral chemistry of this xenolith, such as the low Al₂O₃ concentrations of secondary orthopyroxene, is consistent with other Tietonggou xenoliths (Figure 8). The enrichment of LREE relative to HREE of this xenolith is also a common characteristic in Tietonggou xenoliths (Figure 10b) and the Sr-Nd isotopic composition of this xenolith does not differ too much from that of other Tietonggou xenoliths (Figure 11).

Therefore xenolith LW0006, the most extremely metasomatized sample found so far in the xenolith suite of Tietonggou, provides the opportunity to better constrain the source and environment of this metasomatism, which may have been pervasive in the lithospheric mantle of this age. Since the mineral compositions of the orthopyroxenite portion of this xenolith are similar with those orthopyroxenite veinlets in peridotite xenoliths of Tietonggou, the orthopyroxenite of this xenolith may be a thick melt channel. Xu et al. [2003a] reported that disseminated phlogopite with secondary orthopyroxene and veinlets composed of phlogopite, orthopyroxene, and plagioclase can be observed in dunite xenoliths in the Jin’lin

Figure 10. (a) Spider gram of xenolith LW0006, normalized to the values of the primitive mantle [McDonough and Sun, 1995], compared with the host diores [Chen, 2001] and Fangchen basalts [Zhang et al., 2002]. (b) REE pattern of xenolith LW0006 and other ultramafic xenoliths of Tietonggou [Chen and Zhou, 2004; Xu et al., 2004a], compared with the mantle xenoliths in Cenozoic basalts of Shandong province [Fan et al., 2000]. REE concentrations are normalized to the chondritic values of Anders and Grevesse [1989].

For the concentrations of trace elements in the Cenozoic xenoliths, Cw = Ccpx × modal percent of cpx, where Cw is the element concentration for the whole rock (shown in the figure) and Ccpx is the element concentration for clinopyroxene.

Figure 11. Sr-Nd isotopic composition of xenolith LW0006. (a) Initial value of ⁸⁷Sr/⁸⁶Sr versus ⁴³Nd/⁴⁴Nd. (b) Initial value of ⁸⁷Sr/⁸⁶Sr versus ⁴³Nd/⁴⁴Nd. Star, xenolith LW0006; squares, other ultramafic xenoliths of Tietonggou [Chen and Zhou, 2004]; diamond, mantle xenoliths in Cenozoic basalts of Shandong province [Fan et al., 2000]; all Cenozoic xenoliths plot in the second square except for two pyroxenite xenoliths. Cenozoic basalts, Cenozoic basalts from Shandong province [after Peng et al., 1986]; A, Cretaceous gabbros and basalts from the northern part of west Shandong province [Guo et al., 2001, 2003; Zhang et al., 2003]; B, Cretaceous basalts and andesites from the southern part of west Shandong province [Zhang et al., 2002; Ying, 2002; Qiu et al., 2002]; carbonatites, Cretaceous carbonatites from Laiwu and Zibo [Ying et al., 2004]. High-Mg diorites: 1, Tietonggou pluton [Chen, 2001]; 2, Kuangshan pluton [Chen, 2001]; 3, Jiaoyu pluton [Xu et al., 2004]; 4, Yi’nan pluton [Xu et al., 2004]. Note that two samples with obvious crustal contamination are not included in this figure and Figure 14. Adakitic granites from Tietonggou are from unpublished data of Chen.
high-Mg diorite, an Early Cretaceous pluton in Zibo, west Shandong province. They suggested that these xenoliths might have been metasomatized by some kind of Si- and K-rich liquids. We speculate that the phlogopite might exist before the growth of the secondary orthopyroxene and plagioclase, and we will discuss similar metasomatic phenomena found recently in Tietonggou xenoliths later. Hence ultramafic xenoliths from the Tietonggou diorite of Laiwu and the Jin’lin diorite of Zibo might have undergone similar metasomatism to that observed in xenolith LW0006.

### 6.2. Interactions Between Xenolith and Host Magma

Since the host diorite is Si-oversaturated, metasomatism observed in the xenolith, especially the growth of secondary orthopyroxene could result from interactions between the dioritic magma and the Si-undersaturated peridotite. Tietonggou xenoliths are frequently covered with thin hornblendite selvages. A hornblendite selvage also has been observed in the dunite portion of xenolith LW0006 (Figure 4b), which might be produced by reaction between the host magma and the dunite. The sharp boundary between the host diorite and the orthopyroxenite portion of xenolith LW0006 suggests there might be little reaction between them, since orthopyroxene and phlogopite are Si-saturated. The selvage and veinlet of hornblendite are common in some peridotite xenoliths carried by calc-alkaline andesites [Arai et al., 2003a]. Since the host magma is a highly Si-oversaturated hydrous melt and olivine is highly Si-undersaturated, the reaction between them might produce hornblende quickly at the margin of the xenoliths at shallow depth, which would hamper further reaction between them. Therefore the metasomatism observed in Tietonggou xenoliths must have occurred before the entrainment by the host dioritic magma. The chemical differences between the metasomatic minerals in the xenoliths and the minerals in the host diorite, e.g., plagioclase, support this interpretation.

### 6.3. Metasomatic History

The resorbed shapes of the dunite portions (Figure 2) suggest that the primary lithology of the composite xenolith is dunite, and that a series of metasomatism changed the composition of this specimen resulting in an orthopyroxenite-dominated lithology.

In dunite A, the presence of the composite veinlet (clinopyroxenite + orthopyroxenite) suggests two stages of metasomatism occurring in the same path (Figure 5). The spatial relationship of the different parts of the composite veinlet and the exsolution textures of minerals suggest that the phlogopite- and amphibole-bearing clinopyroxenite veinlet was produced first. A second-stage of metasomatism consumed the early metasomatic minerals and produced the secondary orthopyroxene in the same passage. Mg# values of the secondary orthopyroxene (Mg# = 91.8 – 92.6) are similar to those of the olivine by the orthopyroxenite veinlet (Mg# = 92.3), which suggests that there has been Mg-Fe equilibration (Figure 12).

In dunite B, the replacement relationship between clinopyroxene, phlogopite and orthopyroxene, amphibole, plagioclase suggests that there are at least two stages of metasomatism (Figure 6). Intergranular clinopyroxene and phlogopite were produced by early stage(s) of metasomatism. The later metasomatic event followed the same path as the early metasomatism, and affected the early stage metasomatic minerals, crystallizing orthopyroxene, amphibole, and plagioclase. The similar Mg# values of secondary orthopyroxene and primary olivine, 88.1–88.7 and 88.2, respectively, suggest that they have experienced Mg-Fe equilibration (Figure 12).
[39] All of minerals in the clinopyroxenite of the composite veinlet in Dunite A are enriched in CaO, which suggests that the metasomatic medium was a Ca-rich liquid, such as, e.g., carbonate melts. The presence of phlogopite in the clinopyroxenite veinlet suggests that this metasomatic agent was also enriched in K. The intergranular minerals in dunite B also include phlogopite and clinopyroxene, which suggests that dunite B was also metasomatized by a K- and Ca-rich liquid. The high concentrations of K$_2$O (0.67 wt%) and CaO (2.17 wt%) in the whole rocks suggest that such metasomatism contribute significantly to the chemistry of the orthopyroxenite. The late-stage metasomatism in both dunite A and dunite B are characterized by the growth of secondary orthopyroxene, which suggests that both dunite A and dunite B were metasomatized by Si-rich liquids. Figure 7 shows that the late metasomatism in this part is characterized by the breakdown of phlogopite, the resorption of olivine, and the growth of orthopyroxene and plagioclase, which is consistent with what is seen in dunite A and dunite B. The growth of Na-rich orthopyroxene and Na-rich amphibole, as well as the high Na$_2$O concentration (0.65 wt%) of the whole rock, suggests that the late-stage metasomatic liquids were also enriched in Na$_2$O. Therefore we designate the late-stage metasomatism in the xenolith as Si (Na) metasomatism.

[30] Figure 12 illustrates that phlogopite and orthopyroxene in dunite A and dunite B have experience Mg-Fe equilibration with olivine, although this has not taken place in the orthopyroxenite. In the orthopyroxenite, olivine has a narrow range of Mg$^+$ values (85.5–86.6), whereas both phlogopite and orthopyroxene have broad ranges of Mg$^+$ values, 89.1–92.0 and 85.2–87.9, respectively. We have calculated that the equilibration temperatures of Tietonggou xenoliths are in the range of 690–790°C according to the orthopyroxene Ca thermometer [Brey and Kohler, 1990] and the olivine-spinel Mg-Fe exchange thermometer [Fabries, 1979; Chen and Zhou, 2004]. Under such high-temperature conditions, Mg-Fe exchange between silicate minerals is very rapid and it is easy to obtain Mg-Fe equilibrium in a short time. Therefore the Mg-Fe disequilibrium observed in the orthopyroxenite indicates that Si (Na) metasomatism may have occurred shortly before entrainment of the xenolith in the host magma. The Mg-Fe equilibrium observed in dunite A and dunite B may be due to low orthopyroxene/phlogopite:olivine ratios. It is reasonable to speculate that the ubiquitous heterogeneity of spinel also resulted from Si (Na) metasomatism.

[31] In summary, the petrography, mineral chemistry, and major element compositions provide a clear metasomatic record of the composite xenolith: K (Ca) metasomatism, and Si (Na) metasomatism. K (Ca) metasomatism is characterized by the development of phlogopite-, and amphibole-bearing clinopyroxenite veinlets or intergranular phlogopite (and clinopyroxene). Si (Na) metasomatism is characterized by the growth of secondary orthopyroxene, Na-rich plagioclases (with or without Na-rich amphibole), and the resorption of olivine and decomposition of phlogopite. Si (Na) metasomatism occurred shortly before entrainment of the xenolith. Tietonggou xenoliths are thought to be samples from the crust-mantle transitional zone (Moho) [Chen and Zhou, 2004] or uppermost mantle [Xu et al., 2003b, 2004a]. Deep sourced liquids, which metasomatized this region, might have metasomatized the entire SCLM.

6.4. Subduction-Related Metasomatism: Fluids Versus Melts

[32] The exceptional $\delta^{18}O$ value and exceptionally high concentrations of Na$_2$O, K$_2$O and Al$_2$O$_3$ in this sample suggest a clear contribution of recycled crustal materials in the source. The elemental signatures of the orthopyroxenite portion of the xenolith, such as depletions of Nb, Ta, Ti, and P, and the positive Pb anomaly (Figure 10a), are similar to those of arc volcanics, which suggest that at least one of these three metasomatic events is related to subduction. Since the orthopyroxenite is mainly composed of secondary orthopyroxene, Si (Na) metasomatism is the most likely candidate to contribute to the elevated $\delta^{18}O$ value.

[33] In recent years, subduction-related metasomatism has become better understood through increased xenolith localities in arc settings, where ultramafic xenoliths have been thought to be fragments from a mantle wedge. These localities include the Japanese island arcs [Abe et al., 1998; Arai and Kida, 2000], the Luzon arc of Philippines [Maury et al., 1992; Schiano et al., 1995; Arai and Kida, 2000; Arai et al., 2004], the Colorado Plateau [Smith and Riter, 1997; Smith et al., 1999], the Cascades, USA [Brandon and Draper, 1996; Ertan and Leeman, 1996; Brandon et al., 1999], Mexico [Luhr and Aranda-Gómez, 1997; Blatter and Carmichael, 1998], Papua New Guinea [McInnes and Cameron, 1994; Grégoire et al., 2001; McInnes et al., 2001; Franz et al., 2002],
Southern Patagonia, Argentina \cite{Goring_and_Kay_2000, Laurora_et_al_2001}, the Canadian Cordillera \cite{Peslier_et_al_2002, Kepezhinskas_et_al_1995, Arai_et_al_2003b}, Kamchatka \cite{Kepezhinskas_et_al_1995, Arai_et_al_2003a}, and the Betic Cordillera, southern Spain \cite{Arai_et_al_2003b, Beccaluva_et_al_2004}. Mantle xenoliths from these localities show complicated modal metasomatism, including vein metasomatism, pervasive metasomatism and irregular metasomatism. Some silica-rich glass inclusions, pockets and veinlets have been also found in these mantle xenoliths as residue melts \cite{Schiano_et_al_1995, Ertan_and_Leeman_1996, Eiler_et_al_1998}. These wedge-derived samples provide direct evidence that slab-derived fluids/melts have modified the mantle wedge and have affected the geochemical characteristics of arc volcanics.

Among these wedge-derived samples, secondary orthopyroxenes are common and have been thought to be a mark of Si metasomatism in the subarc mantle. Secondary orthopyroxenes are characterized by a depletion of Al$_2$O$_3$ relative to primitive orthopyroxene. The crystallization of orthopyroxenes suggests that the metasomatic liquids are saturated with silica. Up to now, it has been controversial whether such slab-derived silica-rich liquids are fluids or melts. \cite{McInnes_et_al_2001} found that orthopyroxenes in fluid-metasomatized peridotites are enriched in Mg$^+$ and depleted in Al$_2$O$_3$ compared to anhydrous peridotite, and this trend correlates with an increase in the intensity of fluid:rock interactions. In Figure 13, we illustrate the published chemical data of orthopyroxenes in metasomatized peridotite xenoliths from arc settings, and find that such a trend appears in orthopyroxenes in most cases (Mg$^+$ > 90). In addition, orthopyroxenes with low Mg$^+$ values (85–87) have been found in a few cases, including daughter minerals inside silica-rich melt inclusions in olivine from Philippines xenoliths \cite{Schiano_et_al_1995} and orthopyroxenes in an intensely metasomatized xenolith, with many silica-rich melt inclusions and pockets from the Cascades, USA \cite{Ertan_and_Leeman_1996}. Petrographic evidence shows that there are genetic relationships between low-Mg$^+$ orthopyroxenes and silica-rich melt inclusions. \cite{Carroll_and_Wyllie_1989, Rapp_et_al_1999, Prouteau_et_al_2001} carried out a series of experiments on the interactions between silica-rich melts and peridotites/olivines. These experiments show a clear correlation between the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure_13.png}
\caption{Comparison of the compositions of orthopyroxene (opx) in mantle xenoliths with different tectonic backgrounds. A, opx in Dunite A of xenolith LW0006; B, opx in Dunite B of xenolith LW0006; O, opx in the orthopyroxenite of xenolith LW0006. Primitive opx from Tietonggou xenoliths (this study) show more depleted compositions than Cenozoic xenoliths of the NCC \cite{Rudnick_et_al_2004}. Secondary opx from Tietonggou xenoliths have low Al$_2$O$_3$ signatures, which is similar to those of arc xenoliths, but they have clearly lower Mg$^+$ values than most arc samples. Such signatures have only been found in a few cases, such as 1, daughter mineral inside high-silica glass inclusions in harzburgitic olivine \cite{Schiano_et_al_1995}; 2, metasomatic orthopyroxenite \cite{Ertan_and_Leeman_1996}; and 3, Quartz diorite veins in lherzolite \cite{Arai_et_al_2003b}. Orthopyroxene crystallized in the reaction experiments between silica-rich melts and peridotites/olivines: a, 15 kbar, 900°C and 1000°C, mixture of 60 wt% trondhjemite and 40 wt% olivine, and 7.8 wt% an 9.6 wt% H$_2$O added \cite{Prouteau_et_al_2001}; b, 3.8 Gpa, 1100°C and 1150°C, reaction between partial melts from amphibolitized pillow lava and 16 wt% and 30 wt% depleted peridotite \cite{Rapp_et_al_1999}; other triangles, 850–1100°C, 15 kbar, mixture of 95 wt%, 90 wt% tonalite and 5 wt%, 10 wt% peridotite, and 5–10 wt% H$_2$O added \cite{Carroll_and_Wyllie_1989}.}
\end{figure}
The secondary orthopyroxene of Tietonggou xenoliths is also characterized by low Al$_2$O$_3$ concentrations (Figure 8). In xenolith LW0006, secondary orthopyroxene shows broad range of compositions. Orthopyroxene in the orthopyroxenite has lower Mg$^\#$ values (85.2–87.9) than dunite A (91.8–92.6) and dunite B (88.1–88.7). In Figure 13, orthopyroxenes from the three parts of xenolith LW0006 fall within the experimental range of melt:rock interactions and display the same general trend, which is distinct from the trend suggested for fluid:melt interaction. Arai et al. [2003a] noted that fluid metasomatism is characterized by simple mineral compositions and complicated boundaries between secondary orthopyroxene and primary minerals. In contrast, the metasomatic minerals in xenolith LW0006 not only include orthopyroxene, but also plagioclase, amphibole, zircon, rutile, apatite, etc., which could not have crystallized from fluids. The simple boundaries between secondary orthopyroxene and primary olivine also support melt-induced metasomatism. Consequently, the Si (Na) metasomatic liquids of the Tietonggou xenoliths most likely are slab-derived melts, and not fluids.

Na metasomatism had been recognized in mantle xenoliths from the north Kamchatka arc and is characterized by the growth of Na-rich clinopyroxene and Na-rich plagioclase [Kepezhinskas et al., 1995]. The occurrence of trondhjemitic veins in the xenoliths suggests that these metasomatic liquids are adakitic melts from partial melting of subducted oceanic crust [Kepezhinskas et al., 1995]. Thus the growth of Na-rich plagioclase in Tietonggou xenoliths also suggests that the late-stage metasomatic liquids might be slab-derived melts.

6.5. Metasomatism and Heterogeneity of the SCLM Beneath Shandong Province

Mantle-derived rocks of the Early Cretaceous are prevalent in Shandong province and provide a window to understand the chemical composition of the SCLM beneath this region. In Figure 11b, we illustrate the Sr-Nd isotopic composition of these rocks and divide them into three suites: series A, series B, and series C. Series A includes gabbros and basalts from the northern part of west Shandong (Ji’nan, Zhangqiu, and Zoupin); they have low $^{87}$Sr/$^{86}$Sr (0.70396–0.70580) and low $^{143}$Nd/$^{144}$Nd (0.51140–0.51228) [Guo et al., 2001, 2003; Zhang et al., 2004]. Series B includes basalts, andesites, and lamprophyres from east Shandong and the southern part of west Shandong, and carbonatites of Laiwu and Zibo, with high $^{87}$Sr/$^{86}$Sr (0.70609–0.71177) and low $^{143}$Nd/$^{144}$Nd (0.51149–0.51205) [Zhang et al., 2002; Qiu et al., 2002; Ying et al., 2004; Yang et al., 2004]. Series C are the high-Mg diorite-dominated plutons in west Shandong, which have higher $^{143}$Nd/$^{144}$Nd ratios (0.51167–0.51247) and moderate $^{87}$Sr/$^{86}$Sr ratios (0.70529–0.70740) [Chen, 2001; Xu et al., 2004]. Therefore these three series of rocks can be distinguished by their $^{87}$Sr/$^{86}$Sr ratios.

The SCLM beneath Archean cratons is generally characterized by enriched Sr-Nd isotopic signatures, such as Kapavaal [Walker et al., 1989], Wyoming [Carlson and Irving, 1994], and Siberia [Pearson et al., 1995]. Archean mantle with low abundances of phlogopite (low phlogopite clinopyroxene ratios) can evolve into a mantle with a low $^{87}$Sr/$^{86}$Sr and low $^{143}$Nd/$^{144}$Nd signature, as Rb is fixed in phlogopite whereas Sr, Nd, and Sm are mainly incorporated into clinopyroxene [Schimdt et al., 1999]. Such a Sr-Nd isotopic signature can be found in Early Cretaceous rocks not only from Shandong province, but also many other areas in the NCC, such as the Taihang area, the Yanshan area and the north margin of NCC. Guo et al. [2003] proposed that the SCLM beneath the NCC is characterized by the same isotopic signature, and that mafic rocks with this Sr-Nd isotopic signature, shown as series A in Figure 8b, originate from the uppermost part of an aged and refractory SCLM with a low phlogopite clinopyroxene ratio. Early Cretaceous rocks with high $^{87}$Sr/$^{86}$Sr and low $^{143}$Nd/$^{144}$Nd, shown as series B in Figure 11b, are more typical in Shandong province. The mantle sources for these rocks might have been enriched by the subduction of the Yangtze craton [Qiu et al., 2002; Zhang et al., 2002; Ying et al., 2004] or ancient subduction events [Yang et al., 2004]. It is significant that Laiwu-Zibo carbonatites and Fangcheng basalts not only have extremely enriched Rb, Ba, U and LREE (Figure 10a), but also have high CaO concentrations, 19.6–46.9 wt% and 8.7–10.0 wt%, respectively. Since the REE are mainly incorporated in clinopyroxene whereas Rb, Ba, U are fixed in phlogopite and amphiboles in the upper mantle, it is
reasonable to deduce that the source for series B is vein-plus-peridotite mantle with amphibole- or phlogopite-bearing clinopyroxenite veins [Yang et al., 2004]. Thus the K (Ca) metasomatism observed in Tietonggou xenoliths might be associated with the enriched Sr-Nd isotopic signature of the SCLM beneath the NCC.

Tietonggou diorites, as well as other high-Mg diorites in west Shandong province [Chen, 2001; Xu et al., 2004], have low SiO2 (57–60 wt%), high MgO (>6 wt%) and Mg# values (>0.7), high concentrations of Cr (>500 ppm) and Ni (>150 ppm), enrichments in Sr (>600 ppm) and Ba (>1000 ppm), and high Na2O (3.1–3.4 wt%), K2O (1.8–2.4 wt%), LREE, and La/YbN ratios (>10) [Chen, 2001]. The geochemical characteristics of Tietonggou diorites are similar to those of high-SiO2 adakites, which are broadly thought to be slab melts [Martin et al., 2005]. Besides high-Mg diorites, granitic rocks also exist in the Tietonggou pluton. Tietonggou granites have high SiO2 (70.5–72.0 wt%), high Na2O (4.5–5.2 wt%), Na2O/K2O > 1, high Sr (590–670 ppm), high La/YbN (50–100), and extremely depleted HREE (Yb < 0.3 ppm) and Y (<4 ppm) (unpublished data of Chen). The geochemical characteristics of Tietonggou granites are similar to those of high-SiO2 adakites, which are broadly thought to be slab melts [Martin et al., 2005]. Thus geochemical evidence from the Tietonggou pluton also indicates that the SCLM beneath Laiwu might have been metasomatized by slab melts.

In 206Pb/204Pb versus 87Sr/86Sr and 143Nd/144Nd diagrams, adakitic granites, high-Mg diorites, and xenolith LW0006 of Tietonggou line up along a possible mixing array (Figure 14). The isotopic composition of xenolith LW0006 and its host rocks can be produced by mixing between an enriched mantle with low 206Pb/204Pb and low 143Nd/144Nd, and the adakitic granites with high 206Pb/204Pb and high 143Nd/144Nd. It is evident that other high-Mg diorite-dominated plutons also plot along the possible mixing line of Tietonggou in the 206Pb/204Pb versus 87Sr/86Sr diagram (Figure 14a), but plot under the possible mixing line of Tietonggou in the 206Pb/204Pb versus 143Nd/144Nd diagram (Figure 14b). Each high-Mg diorite-dominated pluton has a broad range of 206Pb/207Pb ratios. Since high-Mg diorites are exceptionally enriched in Sr, crustal assimilation might have less of an affect on their Sr isotopes than their Nd and Pb isotopes. Therefore high-Mg diorites in west Shandong province might have a similar source as the high-Mg diorites of Tietonggou, which were metasomatized by slab melts like adakitic granites of Tietonggou. Xu et al. [2003b, 2004a, 2004c] suggested that the metasomatic agent for Tietonggou xenoliths might be from a recycled continental crust. However, the higher 143Nd/144Nd ratios of adakitic granites, high-Mg diorites of Tietonggou than of other Early Cretaceous mantle-derived rocks in Shandong province do not support such a proposal (Figures 11b and 14b). Thus Si (Na) metasomatism observed in Tietonggou xenoliths provides direct evidence for the genesis of high-MgO diorites in Shandong province.

6.6. Relationship Between Subduction and Lithospheric Transformation

Dating the Mesozoic rocks could provide a temporal framework for the lithosphere thinning.
The direct cause of lithospheric thinning of the SCLM beneath the NCC is a long-term process. High-Mg diorites and adakitic granites in west Shandong, suggests that the SCLM beneath this area was modified by slab-derived melts. Since Si (Na) metasomatism occurred at the peak stage of the lithospheric thinning, subduction might have been involved in the thinning process of the SCLM beneath the NCC.

\[43\] Petrological evidence from a unique composite xenolith in Laiwu diorites reveals a complicated metasomatic history in the SCLM beneath the east NCC, including K (Ca) metasomatism as early stage enrichment, and Si (Na) metasomatism as a late event.

\[44\] Evidence from the mineral chemistry, geochemistry, and Sr-Nd-Pb-O isotopic compositions of the unique xenolith indicate that Si (Na) metasomatism might result from reactions with slab melts, and occur shortly before entrainment by the host magma.

\[45\] Si (Na) metasomatism observed in Tietonggou xenoliths, which are genetically linked with Early Cretaceous high-Mg diorites and adakitic granites in west Shandong, suggests that the SCLM beneath this area was modified by slab-derived melts. Since Si (Na) metasomatism occurred at the peak stage of the lithospheric thinning, subduction might have been involved in the thinning process of the SCLM beneath the NCC.

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