U-Pb zircon ages for a collision-related K-rich complex at Shidao in the Sulu ultrahigh pressure terrane, China

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(Received March 18, 2002; Accepted July 15, 2002)

The Shidao complex at the eastern extremity of the Sulu ultrahigh pressure (UHP) terrane is composed of oldest pyroxene syenite, quartz syenite and youngest granite intrusives of the K-rich shoshonitic series. U-Pb zircon dating yields nearly concordant ages of 225 ± 2, 211 ± 3 and 205 ± 5 Ma for pyroxene syenite, quartz syenite and granite, respectively. The ages closely postdate the 240 to 220 Ma UHP metamorphism and correspond to the rapid cooling and exhumation of UHP rocks. A close genetic relation may exist between the formation of the Shidao intrusives and the continental collision and UHP metamorphism. However, the K-rich Shidao intrusive rocks are different from common syn-collisional granites in association of K-rich and granitic magmatism. A breakoff model is postulated to explain the formation of the complex. The breakoff of the subducting slab caused the rapid exhumation of the UHP terrane. Mantle upwelling resulted in basaltic magmatism and formation of the K-rich complex. Formation of the Shidao complex marked the cessation of the UHP metamorphism and the oldest ages of 225 ± 2 Ma of the complex is the minimum timing for the UHP metamorphism.

INTRODUCTION

The Dabie-Sulu terrane in east central China is known to contain the largest distribution of ultrahigh pressure (UHP) rocks in the world. Coesite-bearing and other UHP rocks are widely distributed in the two terranes (Liou and Zhang, 1995; Okay et al., 1989; Xu et al., 1992; Yang et al., 1993; Ye et al., 2000a). Available age data indicate that the continental collision and UHP metamorphism took place in Early Triassic, around 240 to 220 Ma (e.g., Ames et al., 1993, 1996; Chavagnac and Jahn, 1996; Hacker et al., 1998, 2000; Li et al., 1993a, 1996, 1997, 2000; Rowley et al., 1997). Much research work has been carried out on the tectonic evolution of the orogenic belt (e.g., Cong et al., 1999; Dong et al., 1998; Hacker et al., 1995; Liou et al., 1996; Maruyama et al., 1994; Wang et al., 1992). Collision-related intrusions are one of the main components in many orogenic belts (e.g., Atherton and Ghani, 2002; Davies and von Blanckenburg, 1995; Hansmann and Oberli, 1991; von Blanckenburg, 1992). Study of such intrusions provides important constraints to interaction between subducted continental slab and upper mantle rocks, timing of cessation of subduction and upwelling of the mantle.

Granitic rocks are widely distributed in the
Qinling-Dabie-Sulu orogenic belt. Most of them are post-collisional, emplaced during Early Cretaceous, around 140 to 120 Ma (Chen et al., 1995; Eide et al., 1994; Jahn et al., 1999; Ma et al., 1998; Xie et al., 1996, 2001). Syn-collisional granites have only been identified in South Qinling. Zircons from six high-K calc-alkaline granites gave concordia Triassic U-Pb ages of 220 to 206 Ma (Sun et al., 2002) whereas rapakivi granites were dated at 217 to 210 Ma using zircon U-Pb, biotite Ar-Ar and Rb-Sr mineral isochron (Lu et al., 1999). However, syn-collisional intrusion is rare in the Dabie-Sulu terranes. Lin et al. (1992) dated Shidao complex from eastern Sulu terrane and gave whole rock Rb-Sr ages of 220 and 217 Ma. However, they did not relate the origin of the complex to the UHP belt. Guo, J. H. et al. (2001) reported two zircon U-Pb ages for one intrusion of the Shidao complex.

In this paper, we report new zircon U-Pb ages for three units of the Shidao complex in the Sulu region and discuss their origin and geological implications.

**GEOLOGIC SETTING**

The Qinling-Dabie-Sulu orogenic belt in the central China was formed by collision between the North China and Yangtze blocks during the Triassic. The Sulu terrane was offset by the sinistral Tanlu Fault by about 500 km to the north (Xu and Zhu, 1994; Fig. 1). The terrane is generally divided into a high-pressure blue schist unit in the south and an UHP unit in the north (inset of Fig. 1). Similar to the Dabie terrane, the Sulu UHP unit is represented by a metamorphic complex composed mainly of granitic gneiss, granulite and subordinate eclogite, schist, amphibolite, marble and quartzite. These rocks were subjected to Triassic UHP metamorphism (Carswell et al., 2000; Ye et al., 2000b). Eclogites, including coesite-, and coesite-pseudomorph-bearing eclogites, and serpentinized peridotites occur as “enclaves” in gneisses or as nodules in marbles. The Sulu terrane is intruded by abundant Mesozoic granitic plutons, most of which are Late Jurassic to Early Cretaceous in age (Shandong, 1991).
The Shidao complex is located in the eastern extremity of the Sulu terrane (Fig. 1) and intruded into the granitic gneisses. The complex is composed of three intrusions: the Jiazishan pyroxene syenite, the Renheji quartz syenite and the Chashan granite (Fig. 1).

The pyroxene syenite body is situated in the northeastern part of the complex (Fig. 1). The pyroxene syenite is composed of K-feldspar (55–70%), plagioclase (18–27%), small amount of quartz (less than 4%), biotite (2–7%) and variable amount of amphibole and pyroxene of up to 14% (Lin et al., 1992; Shandong, 1991). Rocks cropped out in the central part of the intrusion is porphyritic with coarse-grained matrix of K-feldspar, plagioclase and small amount of pyroxene and biotite, containing K-feldspar phenocryst as large as 1 × 2 cm. Pyroxene syenite with trachyidot structure occurs in the northeastern part of the intrusion where feldspars have a subparallel disposition, parallel to the contact of the intrusion and the granitic gneiss. The relation between the two kinds of pyroxene syenite with different textures is unknown because the contact between them is covered by Quaternary sediments. The sample studied here (97CK28) is a porphyritic pyroxene syenite collected from the central part of the intrusion (Fig. 1).

The quartz syenite intrusion is in the middle of the complex (Fig. 1). The rocks are composed of alkaline feldspar (up to 75%), plagioclase (10%), quartz (10–15%), and minor biotite, amphibole of up to 2% (Lin et al., 1992; Shandong, 1991). Sample 97CK29 collected in the eastern periphery of the body (Fig. 1) is porphyritic with phenocrysts mainly of medium-grained K-feldspar, sodic plagioclase and quartz, mafic minerals are rare. Some K-feldspar has been replaced by albite.

The granite is located in the southeastern part of the complex (Fig. 1) and composed of perthite (up to 66%), plagioclase (7–26%), quartz (25%) and minor biotite and amphibole (about 1–2%). Miariolitic texture is common (Lin et al., 1992; Shandong, 1991). Sample 97CK30 from the southern part of the intrusion (Fig. 1) is coarse-grained and composed of K-feldspar, plagioclase, quartz and small amount of amphibole, biotite and titanite.

Garganite and syenite-aplite dykes occur in the pyroxene syenite and quartz syenite intrusions. Granite-aplite, syenite-porphyry and granite-porphyry dykes cut quartz syenite and granite. Eclogite xenolith in these dykes was reported by Lin et al. (1992).

Intrusive relations are well established in the field. The quartz syenite clearly intrudes into porphyritic pyroxene syenite along the southwestern part of the later, with sharp contact (Fig. 1). Numerous dykes of quartz syenite cut pyroxene syenite, and the later forms many xenoliths with the long dimension ranging from tens of meters near the contact to only several centimeters far away from the contact. Quartz decreases in the quartz syenite dykes along the contact with pyroxene syenite. Xenoliths of pyroxene syenite are “digested” by the quartz syenite magma to different degrees. Contact between quartz syenite and granite is covered by Quaternary sediments and can not be observed. However, xenoliths of pyroxene syenite and quartz syenite can be found in the granite. These xenoliths are also “digested” by the granite magma. These features are used to establish the relative chronology of intrusions: from pyroxene syenite to quartz syenite to granite. Gabbro xenoliths were found in pyroxene syenite and quartz syenite, the biggest one is about 300 m long, while the small ones are a few centimeters across, that suggested an even earlier gabbroic magmatism.

According to classification of igneous rocks using major elements (Middlemost, 1994), gabbro enclaves plot near the junction of foid gabbro, monzogabbro, foid monzodiorite and monzodiorite fields; pyroxene syenite in monzonite and syenite fields; quartz syenite in syenite and quartz monzonite fields and granite in quartz monzonite and granite fields (Fig. 2a; Lin et al., 1992; Shandong, 1991; Xie, 1998). The three rock units have high K$_2$O contents of 4.22 to 8.65% at 48.60 to 60.85% SiO$_2$, 5.80 to 6.66% at 61.60 to 69.18% SiO$_2$ and 5.15 to 6.07% at
67.22 to 73.54% SiO₂ for the pyroxene syenite, quartz syenite and granite, respectively (Fig. 2b; Lin et al., 1992; Shandong, 1991; Xie, 1998). Thus, they belong to the shoshonitic series.

**METHODS AND RESULTS**

Zircons were extracted from samples of about 10 kg by table concentrator, panning and hand picking. U-Pb isotope analysis was done at the Tianjin Institute of Geology and Mineral Resources. A modified chemical procedure of Krogh (1973) was used to dissolve the zircons in concentrated HF and HNO₃ for about 48 hours at 195°C in teflon pressure bombs. The solutions were then spiked with a mixed ²⁰⁵Pb-²³⁵U tracer for isotope dilution and Pb isotope ratio measurements. Pb and U isotopic ratios were measured on a VG-354 mass spectrometer with a Daly-type detector in a dynamic mode. Pb isotopic ratios were corrected for fractionation, total analytical blank, initial common Pb and the spike. The total blank of the procedure is less than 30 pg for Pb and 1 pg for U. The Pb isotopic ratios of the blank are ²⁰⁶Pb/²⁰⁴Pb = 17.97, ²⁰⁷Pb/²⁰⁴Pb = 15.55, ²⁰⁸Pb/²⁰⁴Pb = 37.71, which are typical of Pb found in the lab.

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**Fig. 2.** (K₂O + Na₂O) vs. SiO₂ (a) and K₂O vs. SiO₂ (b) plot for the three rock units of the Shidao complex (After Middlemost, 1994; Rickwood, 1989). Data were taken from Lin et al. (1992), Shandong (1991) and Xie (1998). FMS = Foid monzosyenite; FMD = Foid monzodiorite; FG = Foid gabbro; M = Monzonite; MD = monzodiorite; MG = Monzogabbro; QM = Quartz monzonite; GD = gabbroic-diorite.
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reagents. Isotopic compositions of the initial Pb are estimated from feldspars of Mesozoic granites in the Dabie-Sulu terranes (\(\text{^{206}Pb/^{204}Pb} = 16.66 \pm 0.64\), \(\text{^{207}Pb/^{204}Pb} = 15.41 \pm 0.07\), \(\text{^{208}Pb/^{204}Pb} = 37.68 \pm 0.70\); Zhang, 1995). The data were reduced following the procedure of ISOPLOT ver. 2.92 (Ludwig, 1994). The uncertainties reported for the ages are 95% confidence limits. The U-Pb analytical results are listed in Table 1 and shown as isotope plots in Fig. 3. In Table 1, only the \(\text{^{206}Pb/}\)
Table 1. U-Pb isotopic data for zircons from the Shidao complex in the Sulu terrane

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Properties</th>
<th>Wgt.</th>
<th>U (ppm)</th>
<th>Pb (ppm)</th>
<th>(^{206}\text{Pb} / ^{238}\text{U})</th>
<th>(^{207}\text{Pb} / ^{235}\text{U})</th>
<th>(^{208}\text{Pb} / ^{232}\text{U})</th>
<th>(^{207}\text{Pb} / ^{206}\text{Pb})</th>
<th>(^{206}\text{Pb} / ^{238}\text{U})</th>
<th>(^{208}\text{Pb} / ^{232}\text{U})</th>
</tr>
</thead>
<tbody>
<tr>
<td>97CK28</td>
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<tr>
<td>2</td>
<td>eu.; s.p.; br.</td>
<td>15(1)</td>
<td>628</td>
<td>34</td>
<td>192.6</td>
<td>2.011</td>
<td>0.0353 ± 5</td>
<td>0.2345 ± 70</td>
<td>0.0482 ± 12</td>
<td>224</td>
</tr>
<tr>
<td>4</td>
<td>p.c.; gr.; br.</td>
<td>20(2)</td>
<td>387</td>
<td>31</td>
<td>73.96</td>
<td>1.341</td>
<td>0.0362 ± 8</td>
<td>0.2649 ± 342</td>
<td>0.0531 ± 66</td>
<td>229</td>
</tr>
<tr>
<td>B1</td>
<td>eu.; gr.; co.; br.</td>
<td>10(1)</td>
<td>807</td>
<td>45</td>
<td>195.2</td>
<td>1.816</td>
<td>0.0351 ± 5</td>
<td>0.2312 ± 59</td>
<td>0.0477 ± 9</td>
<td>223</td>
</tr>
<tr>
<td>Z1</td>
<td>su.; s.p.; br.</td>
<td>20(1)</td>
<td>879</td>
<td>40</td>
<td>855</td>
<td>2.556</td>
<td>0.0356 ± 4</td>
<td>0.2512 ± 55</td>
<td>0.0512 ± 9</td>
<td>225</td>
</tr>
<tr>
<td>Z2</td>
<td>su.; s.p.; br.</td>
<td>20(1)</td>
<td>919</td>
<td>43</td>
<td>566.7</td>
<td>2.598</td>
<td>0.0357 ± 4</td>
<td>0.2485 ± 33</td>
<td>0.0505 ± 5</td>
<td>226</td>
</tr>
<tr>
<td>97CK29</td>
<td></td>
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<td></td>
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<tr>
<td>3</td>
<td>p.c.; p.</td>
<td>15(3)</td>
<td>170</td>
<td>7.6</td>
<td>376.7</td>
<td>2.396</td>
<td>0.0329 ± 16</td>
<td>0.2266 ± 172</td>
<td>0.0500 ± 27</td>
<td>209</td>
</tr>
<tr>
<td>B1</td>
<td>eu.; s.p.; br.</td>
<td>15(5)</td>
<td>704</td>
<td>30</td>
<td>543.8</td>
<td>3.153</td>
<td>0.0333 ± 1</td>
<td>0.2235 ± 17</td>
<td>0.0487 ± 2</td>
<td>211</td>
</tr>
<tr>
<td>B2</td>
<td>eu.; l.p.; p.</td>
<td>15(5)</td>
<td>839</td>
<td>35</td>
<td>772.2</td>
<td>3.207</td>
<td>0.0344 ± 3</td>
<td>0.2404 ± 36</td>
<td>0.0507 ± 5</td>
<td>218</td>
</tr>
<tr>
<td>Z1</td>
<td>su.; s.p.; ye.</td>
<td>15(1)</td>
<td>936</td>
<td>40</td>
<td>636.3</td>
<td>3.258</td>
<td>0.0348 ± 3</td>
<td>0.2429 ± 34</td>
<td>0.0507 ± 5</td>
<td>220</td>
</tr>
<tr>
<td>Z2</td>
<td>eu.; s.p.; ye.</td>
<td>20(1)</td>
<td>460</td>
<td>19</td>
<td>929</td>
<td>3.527</td>
<td>0.0348 ± 4</td>
<td>0.2388 ± 51</td>
<td>0.0498 ± 5</td>
<td>220</td>
</tr>
<tr>
<td>Z3</td>
<td>eu.; s.p.; ye.</td>
<td>15(1)</td>
<td>837</td>
<td>37</td>
<td>698.0</td>
<td>2.849</td>
<td>0.0349 ± 3</td>
<td>0.2443 ± 37</td>
<td>0.0507 ± 5</td>
<td>221</td>
</tr>
<tr>
<td>97CK30</td>
<td></td>
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</tr>
<tr>
<td>1</td>
<td>eu.; l.p.; br.</td>
<td>20(4)</td>
<td>645</td>
<td>27</td>
<td>1638</td>
<td>2.355</td>
<td>0.0327 ± 3</td>
<td>0.2241 ± 23</td>
<td>0.0497 ± 5</td>
<td>207</td>
</tr>
<tr>
<td>2</td>
<td>eu.; l.p.; in.; br.</td>
<td>15(4)</td>
<td>1076</td>
<td>42</td>
<td>47188</td>
<td>2.821</td>
<td>0.0321 ± 3</td>
<td>0.2228 ± 34</td>
<td>0.0503 ± 4</td>
<td>204</td>
</tr>
<tr>
<td>C1</td>
<td>eu.; s.p.; br.</td>
<td>15(6)</td>
<td>1622</td>
<td>67.9</td>
<td>1324</td>
<td>2.342</td>
<td>0.0322 ± 4</td>
<td>0.2256 ± 30</td>
<td>0.0504 ± 4</td>
<td>204</td>
</tr>
<tr>
<td>C2</td>
<td>eu.; l.p.; br.</td>
<td>20(8)</td>
<td>2037</td>
<td>90.9</td>
<td>680.0</td>
<td>2.704</td>
<td>0.0350 ± 1</td>
<td>0.2438 ± 14</td>
<td>0.0505 ± 2</td>
<td>222</td>
</tr>
<tr>
<td>Z1</td>
<td>eu.; s.p.; ye.</td>
<td>20(1)</td>
<td>999</td>
<td>46</td>
<td>828.9</td>
<td>2.318</td>
<td>0.0351 ± 2</td>
<td>0.2458 ± 28</td>
<td>0.0507 ± 4</td>
<td>223</td>
</tr>
<tr>
<td>Z2</td>
<td>eu.; s.p.; ye.</td>
<td>15(1)</td>
<td>857</td>
<td>39</td>
<td>943.5</td>
<td>2.371</td>
<td>0.0349 ± 3</td>
<td>0.2383 ± 37</td>
<td>0.0495 ± 5</td>
<td>221</td>
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</tbody>
</table>

\(^{(1)}\text{eu.} = \text{euhehal crystal}; \text{su.} = \text{subhedral crystal}; \text{p.c.} = \text{part of crystal}; \text{gr.} = \text{granular grain}; \text{p.s.} = \text{short prismatic}; \text{l.p.} = \text{long prismatic}; \text{co.} = \text{corrosion pit on the surface}; \text{in.} = \text{inclusion inside the zircons}; \text{p.} = \text{light pink}; \text{br.} = \text{brown}; \text{ye.} = \text{yellow}; \text{all samples are transparent.}

\(^{(2)}\text{Estimated weight, number in parentheses is the number of zircon grains analyzed.}

\(^{(3)}\text{Measured value, corrected for mass fractionation only.}

\(^{(4)}\text{Corrected for mass fractionation and a total analytical Pb blank.}

\(^{(5)}\text{Radiogenic ratios, corrected for mass fractionation, a total analytical Pb blank and initial common Pb.}

\(^{(6)}\text{Calculated ages from corresponding radiogenic ratios (in Ma), assuming } \lambda_{238}^{{\text{U}}} = 1.55125 \times 10^{-10} \text{ yr}^{-1} \text{ and } \lambda_{235}^{{\text{U}}} = 9.8485 \times 10^{-10} \text{ yr}^{-1} \text{ (Steiger and Jager, 1977).}
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$^{238}\text{U}$ ages are listed since the $^{207}\text{Pb}/^{235}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ages are not applicable to young, lower concordia intercepts.

The zircons separated from the pyroxene syenite (97CK28) are transparent and brown in color. They are subhedral to euhedral with the length to width ratios of 1 to 2. Some grains are crystal fragments. The grain size ranges from about 200 to 400 $\mu$m. Corrosion pits can be seen in some surfaces. Five fractions analyzed are concordant or nearly concordant (Fig. 3a). By weighted averaging of $^{206}\text{Pb}/^{238}\text{U}$ ages ($t_{206}$), a weighted average $t_{206}$ age of $225 \pm 2$ Ma with MSWD value of 1.5 was obtained (Fig. 3b). This apparent age is interpreted as the crystallization time of the pyroxene syenite intrusion.

The zircons isolated from the quartz syenite (97CK29) are transparent, yellow, brown to light pink in color, subhedral to euhedral with the length to width ratios of about 1.5 to 2.5. The lengths of crystal range from about 120 to 350 $\mu$m and a few grains are fragments of crystals. Six fractions were analyzed. Five fractions are concordant and the other plotted close to the concordia (Fig. 3c). The $^{206}\text{Pb}/^{238}\text{U}$ ages of the 6 fractions form two groups: $220 \pm 2$ Ma (MSWD = 1.3) and $211 \pm 1$ Ma (MSWD = 0.2; Fig. 3d). The apparent ages do not correlate with the color and crystal form of zircons. The older age of $220 \pm 2$ Ma is close to the $225 \pm 2$ Ma for the pyroxene syenite (97CK28) and is thus interpreted as the zircon xenocryst from the pyroxene syenite. Abundant pyroxene syenite xenoliths being digested to different degrees and of different sizes in quartz syenite supports this explanation. The younger age of $211 \pm 1$ Ma is interpreted as the crystallization age of the quartz syenite intrusion.

The zircons separated from the granite (97CK30) are transparent, yellow to brown in color, euhedral with the length to width ratios of about 1.5 to 4. The lengths of crystal range from about 150 to 350 $\mu$m. Six fractions were analyzed and are all concordant (Fig. 3e). The $^{206}\text{Pb}/^{238}\text{U}$ ages of the 6 fractions form two groups: $222 \pm 2$ Ma (MSWD = 1.3) and $205 \pm 5$ Ma (MSWD = 5.4; Fig. 3f). Similar to the 97CK29, the older apparent age of $222 \pm 2$ Ma agrees with the age of $225 \pm 2$ Ma for the pyroxene syenite (97CK28) within analytical uncertainty and is thus interpreted as the captured zircon from the pyroxene syenite. The younger age of $205 \pm 5$ Ma is interpreted as the crystallization age of the granite intrusion.

The ages obtained here agree with the intrusive sequence observed in the field.

**DISCUSSION**

Comparing with previous work

Our U-Pb ages agree with existing Rb-Sr results by Lin et al. (1992) who dated two bodies of the Shidao complex by using Rb-Sr technique. They report a whole rock-biotite isochron age of $220 \pm 13$ Ma for pyroxene syenite intrusion. Although the isochron has a large scatter with MSWD of 60 (re-calculated using ISOPLOT; Ludwig, 1994), it is nevertheless compatible with the U-Pb zircon age of this work. The Rb-Sr granite data give a linear array in $^{87}\text{Sr}/^{86}\text{Sr}$ against $^{87}\text{Rb}/^{86}\text{Sr}$ plot that would correspond to an age of $217 \pm 3$ Ma (Lin et al., 1992; re-calculated using ISOPLOT, Ludwig, 1994). This is close to the U-Pb zircon age of the intrusion.

Guo, J. H. et al. (2001) reported zircon U-Pb ages of $212 \pm 1$ and $209 \pm 7$ Ma for Jiazishan pyroxene syenite. These ages are about 15 Ma younger than the present result for the same intrusion by unknown reason.

**Slab breakoff model**

The location just in the middle of the UHP belt and formation closely after UHP metamorphism led us to conclude that Shidao complex is genetically related to the Triassic continent-continent collision taken place at the Dabie-Sulu orogenic belt and is a syn-collisional intrusive complex. However, most syn-collisional granites show characteristics reflecting metasomatism caused by fluid from subducted slab and crustal melting. K-rich Shidao intrusives do not resemble such rocks.

Davies and von Blanckenburg (1995) put forward a slab breakoff model to explain the syn-
collisional magmatism associated with deep subduction of continental crust and UHP metamorphism. According to this model, when the continental lithosphere was subducted, opposing buoyancy force led to an extensional deformation in the subducted slab, resulting in a narrow mode of deformation in the subducted slab and slab breakoff. Following the slab breakoff, the asthenospheric mantle upwelled into the narrow rift, resulting in partial melting of the previously metasomatised overriding mantle lithosphere, producing mafic magmatism (Davies and von Blanckenburg, 1995). Experimental studies predicted that deeply subducted crustal rocks would develop K-rich fluids. Such fluids could cause metasomatism of the overriding lithospheric mantle (Schreyer et al., 1987). The melts could be alkaline to ultrapotassic from small degree melting or calc-alkaline from slightly higher degree melting of more fertile or hydrated peridotite (Atherton and Ghani, 2002). These magmas will rise into the crust and induce crustal melting to produce granitic magma (Davies and von Blanckenburg, 1995). Contemporaneous to the mafic-granitic magmatism, the UHP rocks in the subducted slab started to exhum and the terrane uplifted because of the loss deeply subducted part of the slab and the increasing buoyancy (Davies and von Blanckenburg, 1995). Rapid cooling “froze” the isotopic composition equilibrated in the high temperature, which recorded the time of peak UHP metamorphism and the beginning of exhumation of the UHP rocks and uplifting of the terrane.

The origin of syn-collisional magmatism in the Alps (Davies and von Blanckenburg, 1995; von Blanckenburg and Davies, 1995), in South Karakorum and South Tibet (Maheo et al., 2002), and in Scotland and Donegal, Ireland (Atherton and Ghani, 2002) was successfully explained by using this model. Except for timing of magmatism, the most important feature of the magmatic expression of slab breakoff is association of basaltic (lamprophyric to high-K calc-alkaline) and granitic magmatism (Atherton and Ghani, 2002).

Spatial and temporal relation with respect to the orogeny

In the Alps, continental subduction at ca. 55–45 Ma followed by lamprophyric-granitic magmatism between 43 and 25 Ma (Davies and von Blanckenburg, 1995; von Blanckenburg and Davies, 1995). While in the Scotland and Ireland, magmatism of 435–390 Ma in age (maxima at 410–400 Ma) occurred after closure of Iapetus Ocean (Atherton and Ghani, 2002).

Detailed Sm-Nd and zircon U-Pb dating of eclogites and other UHP rocks from the Dabie-Sulu terranes show that peak UHP metamorphism took place around ca. 240 to 220 Ma (Ames et al., 1993, 1996; Chavagnac and Jahn, 1996; Li et al., 1993a, 2000; Hacker et al., 1998). However, a few results gave younger or older ages (Ames et al., 1993; Hacker et al., 1998; Okay et al., 1993). From Sm-Nd and Rb-Sr dating of the UHP rocks from Shuanghe, Dabie terrane, Li et al. (2000) suggested that the UHP rocks experienced two episodes of rapid cooling which correspond to fast exhumation of the terrane. They suggested that the first rapid cooling took place immediately after UHP metamorphism and the second at 180 to 170 Ma. Most of the age determinations for the UHP rocks in Dabie-Sulu terranes have been done on rocks from the Dabie terrane. There are only a few ages for the Sulu region. Ames et al. (1996) dated an eclogite from western part of the Sulu terrane and obtained a zircon U-Pb age of 217.1 ± 8.7 Ma. A gneiss at Yankou in central Sulu gave a zircon U-Pb age of 220 Ma (Li et al., 1993b, 1997). These data suggest that the peak metamorphism took place at the same time in both Dabie and Sulu terranes. Presence of coesite and other UHP minerals suggests rapid cooling after the peak metamorphism for most Sulu terrane. Therefore, UHP rocks from the Sulu and Dabie terranes probably share the similar first cooling histories.

The formation of the pyroxene syenite closely postdated the regional UHP metamorphism. The crystallization ages of the quartz syenite and granite were about 10 to 20 Ma later than the peak
UHP metamorphism and corresponded to the first stage of fast cooling of the UHP rocks and rapid exhumation of the terrane.

**K-rich syenitic and granitic magmatism**

In the Alps, the duration of the Tertiary lamprophyric-granitic magmatism was 17 Ma, while in the Scotland and Ireland, syn-collisional magmatism lasted for about 45 Ma. At Shidao magmatism lasted for about 20 Ma. This age difference is consistent with slab breakoff model (Davies and von Blanckenburg, 1995).

K-rich pyroxene syenite was formed either by melts from metasomatised lithospheric mantle or by calc-alkaline basaltic magma that crystallized under high pressure (10 kbar) and water-deficient conditions (Meen, 1987). Preliminary work shows a very negative $\varepsilon_{\text{Nd}}(T)$ values of $-16.0$ for pyroxene syenite (Xie, 1998), suggesting no component of asthenosphere and supporting a derivation from enriched old lithosphere of the North China craton, the overriding plate (Guo, F. et al., 2001; Xu, 2001). Quartz syenite and granite also give negative $\varepsilon_{\text{Nd}}(T)$ values of $-15.6$ and $-15.7$, respectively (Xie, 1998). This suggests that the three intrusions of the Shidao complex probably shared a common source. Quartz syenite and granite were possibly formed by fractional crystallization of the syenitic magma because of the identical $\varepsilon_{\text{Nd}}(T)$ values. On the other hand, basaltic magma that intruded into the crust could also lead to granitic magmatism at the crustal depths (Huppert and Sparks, 1988; Davies and von Blanckenburg, 1995). The possibility that the granite of Shidao was formed by crustal melting cannot be ruled out since $\varepsilon_{\text{Nd}}$ (220 Ma) values of regional gneisses of the Dabie terrane concentrated in the $-10$ to $-25$ range (Chen and Jahn, 1998).

The detail model on the formation of the Shidao complex merits further detailed investigation.

As discussed above, the overall feature of the Shidao complex fit well into the scenario of slab breakoff model (Davies and von Blanckenburg, 1995; Li et al., 2001).

Formation of the Shidao complex signals the cessation of the continental collision and the compressive tectonics and marks the onset of the extensional tectonics and exhumation of the UHP rocks. The oldest age of the K-rich complex (225 ± 2 Ma for the pyroxene syenite) provides the minimum estimate for the age of the UHP metamorphism.

**Comparison with other parts of the orogenic belt**

Syn-collisional granites have been found in the Qinling terrane (Lu et al., 1999; Sun et al., 2002). They are high-K calc-alkaline and posses characteristics of crustal melts (Sun et al., 2002; Zhang, 1994). Using breakoff model, Sun et al. (2002) suggested that these intrusions could form by melting of the crust induced by intrusion of basaltic magma due to upwelling of the asthenosphere. Existence of large syn-collisional granite belt suggests that breakoff happened at a shallow depth which disturbed the asthenosphere greatly and led to the large scale melting of the crust.

Since there was no report of syn-collisional intrusions in the Dabie-Sulu orogenic belt, Davies and von Blanckenburg (1995) suggested that breakoff in Dabie-Sulu belt took place at great depths (>130 km) and the upwelling asthenosphere might not lead to a significant thermal perturbation of the distant lithosphere of the overriding plate. The new U-Pb zircon ages reported here for the Shidao complex in the Sulu region suggests that breakoff may not take place in such a great depth for the Sulu terrane, at least in the Shidao region.

According to the breakoff model, heat pulse by upwelling asthenosphere would produce separate intrusions along the strike of the orogenic belt at surface (Atherton and Ghani, 2002). Other slab breakoff related syn-collisional intrusions might exist in the Sulu region. Search for such intrusions in the Dabie and Sulu terranes is being carried out. Priority should be given to K-rich rock-granite association(s) similar to the Shidao complex (pyroxene syenite, amphibole-bearing syenite, quartz syenite and granite) in the Sulu region.
CONCLUSIONS

Located in the most eastern corner of the Sulu UHP terrane, the Shidao complex gave U-Pb zircon ages ranging from 225 ± 2 to 205 ± 5 Ma which are very close to the ages of the UHP metamorphism and correspond to the first stage of rapid cooling and exhumation of the UHP rocks in the Dabie-Sulu orogenic belt. The Shidao complex is the first identified collision-related intrusive complex in the eastern Sulu terrane although the syn-collisional granites have been observed in the Qinling region. The K-rich Shidao intrusives were formed in an extensional environment by partial melting of the lithosphere of the overriding slab and was induced by upwelling of the asthenosphere following the breakoff. Formation of the Shidao complex marks the cessation of the continental collision and UHP metamorphism. The oldest intrusive ages of 225 ± 2 Ma are similar to the minimum ages of the UHP metamorphism.

Acknowledgments—We would like to thank Prof. Chang Y. F. (Department of Land and Resources of Anhui Province), Prof. Deng J. F. (China University of Geosciences, Beijing), Prof. Zheng Y. F. (University of Science and Technology of China) and Prof. Jahn B. M. (University of Rennes 1, France) for constructive discussion. Thoughtful journal reviews by Dr. Liou J. G. and Dr. Turec A. helped us clarify many ambiguities. This work is supported by the former Ministry of Geology and Mineral Resources of China (grant 9501102-3-2), the Major State Basic Research Program of China (G1999075503) to Chen J. F. and Chosun University Funds (2000) to Park Young Seog.

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