LETTER

Zircon U–Pb age of granitoids in the Maizuru Belt, southwest Japan and the southernmost Khanka Massif, Far East Russia

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The Maizuru Belt in southwest Japan and the Khanka Massif in Far East Russia include both Siluro–Devonian and Permo–Triassic granitoids. In order to elucidate the simultaneity of granitoid magmatism in the Maizuru Belt and the Khanka Massif, we investigated zircon U–Pb ages using LA–ICP–MS for granitoid samples from the Maizuru area in the northern zone of the Maizuru Belt and from the Vladivostok area in the southernmost part of the Khanka Massif. Five granitoid samples from the Vladivostok area yielded ages of 422.2 ± 2.5 Ma, 260.7 ± 3.1 Ma, 301.7 ± 2.4 Ma, 249.7 ± 3.5 Ma, and 431.9 ± 2.7 Ma. Additionally, a porphyry sample yielded an age of 423.7 ± 3.2 Ma. Four granitoid samples from the Maizuru area yielded ages of 291.6 ± 4.3 Ma, 443.8 ± 4.1 Ma, 279.7 ± 2.4 Ma, and 259.0 ± 3.0 Ma. In reference to the coexistence of the Triassic sedimentary sequence and Siluro–Devonian and Permo–Triassic granitoids across the Sea of Japan, it seems that there were strong relationships between the northern zone of the Maizuru Belt and the southernmost part of the Khanka Massif. Our data provide additional evidence to support a geological connection between southwest Japan and the Vladivostok area before the Miocene opening of the Sea of Japan.

Keywords: Zircon age, LA–ICP–MS, Granitoids, Maizuru Belt, Khanka Massif

INTRODUCTION

Paleomagnetic and age data of Neogene volcanic rocks in Japan have revealed that the Japanese Islands were located along the eastern margin of the Asian continent until the Miocene opening of the Sea of Japan, which is thought to be related to multi-axis back arc basin spreading (e.g., Otofuji and Matsuda, 1983). Although many researchers accept this theory nowadays, there are some reconstruction models that depict the paleogeographic location of the Japanese Islands before the opening of the Sea of Japan (e.g., Otofuji et al., 1985; Golozoubov et al., 1999). Some researchers have tried to compare the geologic belts in southwest Japan and Primorsky Krai in Russia (e.g., Yamakita and Otoh, 2000; Kojima et al., 2000). Ishiwatari and Tsujimori (2003) made a speculative correlation of the two areas using ophiolites and blueschists as markers.

Fujii et al. (2008) reported bimodal zircon U–Pb ages of granitoids in the northern zone of the Maizuru Belt, which were from the Permo–Triassic and Siluro–Devonian periods. They concluded that these granitoids correlate with granitoids in the South Kitakami Belt, Khanka Massif, and Hida Belt. Recently, Khanchuk et al. (2010) reported similar zircon U–Pb ages of granitoids from the central part of the Khanka Massif. The coexistence of Silurian and Permo–Triassic granitoids in both the Maizuru Belt in southwest Japan and the Khanka Massif in Russia’s Primorsky Krai is suggestive of a geological connection between these two areas, which are now separated by the Sea of Japan. To ascertain the simultaneity of the granitoids, we attempted to obtain the zircon U–Pb ages of samples around Vladivostok in the southernmost part of the Khanka Massif. Additionally, some samples from the northern zone of the Maizuru Belt were also measured for comparison.

GEOLOGICAL SETTINGS

The Maizuru Belt is subdivided into three zones that comprise the southern, central, and northern zones (Kano
et al., 1959). The samples collected for this study from the Maizuru area were from the northern zone. The southern zone consists mainly of basic rocks, which are called ‘Yakuno basic rocks’. The southern zone is thought to be an ophiolite (Ishiwatari, 1985), which has been interpreted to be a fragment of Permian oceanic island arc and marginal basin (Ishiwatari et al., 1990). Ishiwatari and Tsujimori (2003) proposed that the ‘Yakuno ophiolite’ represents a southwestern extension of the Kalinovka ophiolite in Russia’s Primorsky Krai. The central zone consists mainly of Middle Permian to Middle Triassic sedimentary rocks (e.g., Nakazawa et al., 1958; Shimizu et al., 1962). The northern zone consists mainly of granitoids, which are called ‘Yakuno acidic rocks’. The whole rock Rb–Sr isochron ages of the granitoids show a bimodal distribution with peaks at around ~150 Ma and ~300 Ma, and the granitoids are thought to have formed in a crust of matured island arc or continent because of the high initial 87Sr/86Sr ratios (Ikeda and Hayasaka, 1994). The zircon U–Pb ages of the granitoids also indicate bimodality; specifically, the granitoids show ages from the Permo-Triassic (~250 Ma) and Siluro-Devonian (400-450 Ma) (Fujii et al., 2008).

The Khanka Massif has a variety of constituents including Precambrian basement rocks, Riphean to Cambrian clastics, Upper Ordovician to Cenozoic strata (e.g., Khanchuk, 2001; ShcheKa et al., 2001), Permo-Triassic and Siluro-Devonian granitoids (Khanchuk et al., 2010), and ~500 Ma granulites (e.g., Zhou et al., 2010). The Vladivostok area of this study is located in the southernmost part of the Khanka Massif, and it is composed of Early Paleozoic metamorphic rocks in northwestern Ostrov Russkiy (Russian Island), granitoids that are thought to be Permian in age (e.g., Syasko et al., 2002), Permian and Triassic strata, later Mesozoic intrusions, and Cenozoic covers (Fig. 1b).

**SAMPLE DESCRIPTIONS**

Five granitoid samples were collected from the Vladivostok area (VV02, VV05, VV11, VV12, and VV13), and one porphyry sample (VV15) was also collected (Fig. 1b). Sample VV05 was collected from the northern part of Vladivostok, whereas the other samples were collected from the Russian Island. The VV15 sample was collected from a dike intruding into Early Paleozoic metamorphic rocks (Fig. 1b). Additionally, four granitoid samples were collected from the Maizuru area in the northern zone of the Maizuru Belt (MZ01, MZ05, MZ06, and MG01) (Fig. 1c). The samples MZ01 and MZ05 were collected at almost the same points as those of samples KM–4A and KG–1B from Fujii et al. (2008), respectively. The location data are shown in Table 1.

**Granitoid and porphyry from the Vladivostok area**

As outcrops of granitoids are very poor in the Vladivostok area, geological relationships of the collected samples cannot be clarified in the field work.

VV02 is a fine-grained granite. The major minerals are quartz, plagioclase, K-feldspar, and biotite. The mineral grains are 1-2 mm in size. Hornblende is preserved well, but it is present in small amounts. Biotite was totally chloritized. Accessory minerals confirmed included zircon and apatite, which are also present in the following samples.

VV05 and VV11 are coarse-grained granites. The major minerals are around 3 mm in size. Mafic minerals...
are totally replaced by chlorite. The minerals seem to be originally biotite. Pseudomorph of hornblende has not been confirmed.

VV12 is a porphyritic granite with well-developed graphic texture. Plagioclase occurs as phenocrysts. Biotite is totally replaced by chlorite.

VV13 is an equigranular granodiorite. Both biotite and hornblende are totally chloritized or carbonatized.

VV15 is a granodioritic porphyry that intruded into metamorphic rock. Quartz is present as microphenocrysts that are 0.5 mm in size; the matrix is composed mainly of K-feldspar, quartz, and plagioclase. All the mafic pseudomorphs are composed totally of chlorite and epidote. Probable original minerals are hornblende and biotite. The wall rock is a greenschist that consists mainly of plagioclase, amphibole, epidote, carbonate, and chlorite. Plagioclase and mafic pseudomorphs occur as phenocrysts with diameters of 2 mm and 1 mm, respectively.

Granitoid from the Maizuru area

MZ01 is a weakly sheared granodiorite. Major minerals are quartz, plagioclase, and K-feldspar as well as the granitoids described here. Both biotite and hornblende are locally replaced by chlorite. Cataclastic texture is locally developed. Prehnite occurs as a vein mineral. Accessory minerals are zircon and apatite, which are also present in the following granitoid samples. Opaque minerals are more or less present in all the granitoids.

MZ05 is a gneissose-sheared granite. Mylonitization produces a subgrain texture of quartz. Plagioclase and K-feldspar occur occasionally as porphyroclasts. Biotite is totally chloritized.

MZ06 is a porphyritic granite. Quartz and plagioclase occur as porphyroclasts. Graphic texture is observed in many places. Biotite is totally replaced by chlorite.

MG01 is a coarse-grained granite. Biotite is totally replaced by chlorite. Hornblende is decomposed into fine-grained amphibole aggregate. Secondary minerals are chlorite, epidote, and prehnite. Prehnite occurs as a vein, as well as in the sample MZ01.

ANALYTICAL METHODS

The zircon grains for LA-ICP-MS analysis were hand-picked from heavy fractions that were separated from the rock samples by standard crushing and heavy-liquid techniques. Zircon grains from the samples, the zircon standard FC1 (206Pb/238U = 0.1859; Paces and Miller, 1993), and the glass standard NIST SRM610 were mounted in an epoxy resin and polished until the surface was flattened with the center of the embedded grains exposed. Images of both the backscattered electron and cathodoluminescence results were used to select the sites.

Table 1. Locality, rock type, and weighted mean zircon U-Pb ages of the samples

<table>
<thead>
<tr>
<th>Labels</th>
<th>Locality</th>
<th>Rock type</th>
<th>Mean age$^1$ (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VV02</td>
<td>N43°02'08&quot;, E131°53'03&quot;</td>
<td>Granite</td>
<td>422.2± 2.5</td>
</tr>
<tr>
<td>VV05</td>
<td>N43°12'08&quot;, E131°59'20&quot;</td>
<td>Granite</td>
<td>260.7± 3.1</td>
</tr>
<tr>
<td>VV11</td>
<td>N42°58'32&quot;, E131°51'03&quot;</td>
<td>Granite</td>
<td>301.7± 2.4</td>
</tr>
<tr>
<td>VV12</td>
<td>N42°58'55&quot;, E131°45'11&quot;</td>
<td>Granite</td>
<td>249.7± 3.5</td>
</tr>
<tr>
<td>VV13</td>
<td>N43°01'59&quot;, E131°48'54&quot;</td>
<td>Granodiorite</td>
<td>431.9± 2.7</td>
</tr>
<tr>
<td>VV15</td>
<td>N43°02'11&quot;, E131°47'45&quot;</td>
<td>Porphyry</td>
<td>423.7± 3.2</td>
</tr>
<tr>
<td>MZ01</td>
<td>N35°24'14&quot;, E135°08'27&quot;</td>
<td>Granodiorite</td>
<td>291.6± 4.3</td>
</tr>
<tr>
<td>MZ05</td>
<td>N35°25'32&quot;, E135°13'29&quot;</td>
<td>Granite</td>
<td>443.8± 4.1</td>
</tr>
<tr>
<td>MZ06</td>
<td>N35°26'02&quot;, E135°16'39&quot;</td>
<td>Granite</td>
<td>279.7± 2.4</td>
</tr>
<tr>
<td>MG01</td>
<td>N35°28'49&quot;, E135°20'48&quot;</td>
<td>Granite</td>
<td>259.0± 3.0</td>
</tr>
</tbody>
</table>

$^1$ Age errors are 95% confidence interval (1.96σ).

Figure 2. Cathodoluminescence images (CL) of typical zircon grains from the samples. Scale bars are 100 µm across. Circles on the images point to spots analyzed by LA-ICP-MS; the spots are 25 µm across.
**Figure 3.** Tera-Wasserburg U–Pb concordia diagrams and age distribution plot of zircon samples. The uncertainties in the mean $^{238}$U–$^{206}$Pb* ages represent 95% confidence intervals. $^{207}$Pb* and $^{206}$Pb* indicate radiometric $^{207}$Pb and $^{206}$Pb, respectively. (a)-(f) Samples from the Vladivostok area. (g)-(j) Samples from the Maizuru area. Color version is available online from http://japanlinkcenter.org/DN/JST/JSTAGE/jmps/131017.
RESULTS AND DISCUSSION

Most zircon grains in the samples showed magmatic oscillatory zoning and/or sector zoning under the backscattered electron and/or cathodoluminescence images (Fig. 2). Weighted mean ages of zircons in the six samples collected from the Vladivostok area, namely, VV02, VV05, VV11, VV12, VV13, and VV15, were 422.2 ± 2.5 Ma, 260.7 ± 3.1 Ma, 301.7 ± 2.4 Ma, 249.7 ± 3.5 Ma, 431.9 ± 2.7 Ma, and 423.7 ± 3.2 Ma, respectively (Figs. 3a–3f). In comparison, weighted mean ages of zircons in the four samples from the Maizuru area, namely, MZ01, MZ05, MZ06, and MG01, were 291.6 ± 4.3 Ma, 441.9 ± 2.8 Ma, 279.7 ± 2.4 Ma, and 259.0 ± 3.0 Ma, respectively (Figs. 3g–3j). The analytical results are listed in Appendix (Appendix is available online from http://japanlinkcenter.org/DN/JST.JSTAGE/jmps/131017).

Association of Silurian and Permo-Triassic granitoids is known to occur in the central Khanka Massif (Khanchuk et al., 2010). The northern zone of the Maizuru Belt is also composed mainly of Silurian and Permo-Triassic granitoids (Fujii et al., 2008). Ikeda and Hayasaka (1994) and Fujii et al. (2008) proposed that the origin of the northern zone of the Maizuru Belt was the crust of a matured island arc or continent such as the South Kitakami Belt, Khanka Massif, or Hida Belt. Results of this study extend the recognition of the association of Silurian and Permo-Triassic granitoids of the Khanka Massif that are exposed along the Sea of Japan coast. Notably, results of this study show strong relationships between the northern zone of the Maizuru Belt and the Khanka Massif. Although the probable continuity age was before the Triassic, it will be one of the clues to locate southwest Japan before the Miocene opening of the Sea of Japan. Additionally, a porphyry sample VV15 was collected from a dike intruding into the metamorphic rocks, and the age of this sample is thought to be Early Paleozoic. Hence, the obtained age of the porphyry (423.7 ± 3.2 Ma) limits the age of the metamorphic rocks to be before the Silurian period.

The samples MZ01 and MZ05 were collected from the same outcrops as those of KM-4A and KG-1B from Fujii et al. (2008), respectively. The obtained ages were 291.6 ± 4.3 Ma and 441.9 ± 2.8 Ma (this study), whereas Fujii et al. (2008) reported the ages as 424 ± 16 Ma and 405 ± 18 Ma, respectively. Ikeda and Hayasaka (1994) explained that there are at least two types of granitoid in the outcrop of MZ05 (KG-1B): granite and quartz-diorite. Furthermore, their whole rock Rb-Sr isochron ages indicate a bimodal distribution as mentioned above. The age results of this study and previous studies show the same bimodal (Silurian and Permo-Triassic) age distribution of the granitoids in the Maizuru and Vladivostok areas on both sides of the Sea of Japan.

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SUPPLEMENTARY MATERIALS

Appendix and color version of Figures 1 and 3 are available online from http://japanlinkcenter.org/DN/JST.JSTAGE/jmps/131017.

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