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Ages of Igneous Rocks in the Southern Part of Primorye, Far East Russia

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Abstract. In the southern part of Primorye, Far East Russia, Cretaceous and Paleogene igneous rocks are distributed on the eastern side of the continental massif that contains Paleozoic granitoids. Ages of three volcanic rocks and seventeen granitoids in south Primorye were analyzed by U–Th–Pb chemical dating of monazite or thorite using Electron Probe Micro Analysis or U–Pb dating of zircon using Laser Ablation Inductively Coupled Plasma Mass Spectrometry. In addition to the Secondary ionization Mass Spectrometry method, present age determination methods are the most reliable, compared with K–Ar and fission track methods. The south Primorye region was in contact with a part of the Japanese Islands before the opening of the Sea of Japan. As reliable ages are not as common in south Primorye, the present age result will contribute to future comparisons between the Japanese Islands and south Primorye.

Key words: Age, Zircon, Monazite, Samarka, Taukha

Introduction

The Japanese Islands were located at a continental margin and were in contact with the Primorye region, Far East Russia until the opening of the Sea of Japan (e.g. Yamakita & Otoh, 1999; Kojima *et al*., 2000; Ishiwatari & Tsujimori, 2003). In the Japanese Islands, many age data were obtained by various methods; K–Ar (e.g. Kawano & Ueda, 1964, 1966), Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) (e.g. Ishihara & Orihashi, 2015), Sensitive High Resolution Ion Microprobe (SHRIMP) (e.g. Watanabe *et al*., 2000) and Electron Probe Micro Analyser (EPMA) (Yokoyama *et al*., 2016). The granitoids in the Japanese Islands have ages concentrated in the Late Cretaceous to Paleogene. Cretaceous to Paleogene igneous rocks also exist parallel to the tectonic boundaries in Primorye (Khanchuk *et al*., 1996). Many radiometric age data were obtained from all over the Japanese Islands by the most reliable methods such as LA-ICP-MS, SIMS, and EPMA. As far as we know, ages of two granitoids near Nakhodka were obtained by Isotope Dilution Thermal Ionization Mass Spectrometry (Khanchuk et al., 2008). Most of the age data in Primorye were obtained by another method such as K–Ar; therefore, reliable data are still poor in Primorye. In this paper, we obtained the radiometric ages of igneous rocks using EPMA for monazite and thorite and LA-ICP-MS for zircon in Primorye to study the simultaneity of geology in Japan and Primorye.

Geological settings and samples

Primorye, Far East Russia, is tectonically subdivided into the Khanka–Jiamusi Massif, Sergeevka Belt, Samarka Belt, Taukha Belt, Zhurav-

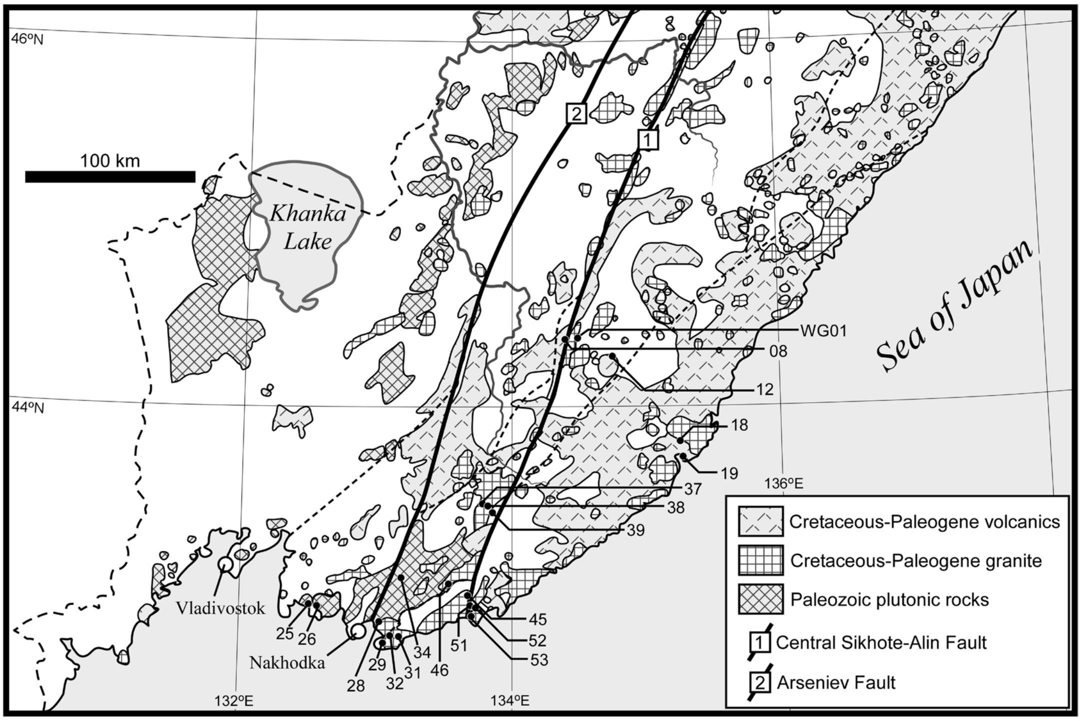

Fig. 1. Distribution map of Paleozoic plutonic rocks and Cretaceous–Paleogene igneous rocks in the southern part of Primorye, Far East Russia (modified after Khanchuk *et al*., 1996).

levka Belt, and Kema Belt (Fig. 1; Khanchuk et al., 1996). The Khanka–Jiamusi Massif and Sergeevka Belt are thought to be parts of the continental massif, whereas the Samarka and Taukha belts are Jurassic and Early Cretaceous accretionary complexes, respectively. Cretaceous and Paleogene igneous rocks intruded into the terranes. Roughly, pre-Jurassic granitoids occur in the Khanka–Jiamusi Massif (Khanchuk *et al*., 2010; Tsutsumi *et al*., 2014). Cambro-Ordovician plutonic rocks exist in the Sergeevka Belt (Khanchuk *et al*., 1996). Early Cretaceous granitoids are distributed mainly in the inland area between the Central Sikhote-Alin and Arseniev faults, whereas Late-Cretaceous to Paleogene granitoids occur in the southeastern coastal area of Primorye. The Zhuravlevka Belt is composed mainly of an Early Cretaceous turbidite sequence with a subordinate amount of flysch-type sediment. The Kema Belt consists of Early Cretaceous island arc rocks and the latest Early Cretaceous volcanic cover (e.g. Khanchuk *et al*., 1996).

Igneous rock samples were collected from southern Primorye (Fig. 1). The rock types, localities, and analyzed minerals are listed in Table 1. The heavy minerals in the samples were separated by the same method described by Yokoyama *et al*. (1990). Among the heavy minerals, zircon, monazite, and thorite are the most important for dating. At first, we tried to obtain monazite (or thorite) U–Th–Pb chemical dating by EPMA, then zircon from U–Pb dating, and LA-ICP-MS was applied to monazite-free samples. Zircon and monazite (or thorite) ages are interpreted as the emplacement age in case of plutonic rocks or the eruption age in case of volcanics.

Most of the samples are granitoid. The WG01 sample is from the main part of the Zhuravlevka Belt. RPM19, 51, 52, and 53 are from the Taukha Belt. RPM25, 26, 28, 34, 37, 38, 39, and 46 are from the Sergeevka Belt. RPM29, 30, 31, and 45

Table 1. Information of detailed locality, age method and age data of the analyzed samples.

Label	Rock type	Localities	analysed mineral	Tectonic division	Age (Ma)
WG01	Weatherd granitoid	N44°22′50.8″ E134°31′18.2″	Tho	ZH	(73.1 ± 2.5)
RPM08	Rhyorite	N44°21′45.4″ E134°24′57.0″	Zrn	(SM)	64.2 ± 2.8
RPM12	Rhyorite	N44°16′29.7″ E134°46′38.9″	Zrn	(ZH)	60.0 ± 0.9
RPM18	Rhyorite	N43°49′19.8″ E135°16′29.8″	Zrn	(TA)	55.0 ± 1.3
RPM19	Granitoid	N43°44′09.2″ E135°15′56.1″	Tho	TA	55.7 ± 0.7
RPM25	Granitoid	N42°55′14.2″ E132°30′57.0″	Mnz	SG	411.7 ± 8.4
RPM26	Granitoid	N42°55′27.0″ E132°34′41.5″	Mnz	SG	512.3 ± 9.1
RPM28	Granitoid	N42°49′47.3″ E133°02′00.0″	Zrn	SG	472.4 ± 4.4
RPM29	Granitoid	N42°43′46.1″ E133°04′24.2″	Zrn	SM	88.1 ± 1.1
RPM31	Granitoid	N42°46′16.9″ E133°11′52.8″	Mnz	SM	71.9 ± 2.5
RPM32	Granitoid	N42°46′55.4″ E133°07′54.7′	Mnz	SM	91.7 ± 4.1
RPM34	Granitoid	N43°05′26.1″ E133°13′01.1″	Zrn	SG	466.3 ± 5.3
RPM37	Granitoid	N43°28′49.6″ E133°47′32.8″	Mnz	SG	89.3 ± 2.7
RPM38	Granitoid	N43°28′19.2″ E133°50′27.2″	Mnz	SG	101.2 ± 1.7
RPM39	Granitoid	N43°26′01.1″ E133°52′02.1″	Mnz	SG	77.3 ± 4.1
RPM45	Granitoid	N42°59′34.4″ E133°41′32.9″	Mnz	SM	105.7 ± 11.4
RPM46	Granitoid	N43°03′17.5″ E133°33′13.8″	Mnz	SG	79.1 ± 4.8
RPM51	Granitoid	N42°55′33.0″ E133°42′16.6″	Mnz	TA	83.1 ± 7.1
RPM52	Granitoid	N42°55′35.3″ E133°44′41.1″	Mnz	TA	78.8 ± 9.0
RPM53	Granitoid	N42°52′46.8″ E133°42′20.8″	Mnz	TA	73.4 ± 2.9

Mnz: monazite, Tho: thorite, Zrn: zircon, TA: Taukha, SG: Sergeevka, SM: Samarka, ZH: Zhuravlevka.

are from the Samarka Belt.

Analytical methods and results

U–Th–Pb chemical dating of monazite

The theoretical basis for the monazite U–Th–Pb chemical age calculation is essentially the same as that developed by Suzuki *et al*. (1991). Monazites were analyzed by the EPMA fitted with a Wavelength Dispersive Spectrometer (WDS), JXA-8230 (JEOL) situated in the National Museum of Nature and Science. Analytical conditions used have been described by Santosh *et al*. (2003). Age calibrations were carefully performed by comparing data obtained by EPMA dating with those acquired by the SHRIMP technique (e.g. Santosh *et al*., 2006). The standard deviation of the age obtained depends mostly on the PbO content in the monazite. The errors for the age are within a few percent for most of the analyzed monazites that were rich in ThO_2. The pooled ages presented in this study were calculated using Isoplot/Ex software (Ludwig, 2003). The uncertainties in the mean ages represent 95% confidence intervals (95% conf.).

Thorite ages were obtained from the weathered granitoid sample WG01 from the Zhuravlevka Belt and the granitoid sample RPM19 from the Taukha Belt. They indicate 73.1 ± 2.5 Ma (MSWD = 10.6) and 55.7 ± 0.7 Ma (MSWD = 1.9), respectively. But the MSWD value of sample WG01 is too large to confirm the age value. Monazite ages of granitoid samples from the Sergeevka Belt of RPM25, 26, 37, 38, 39, and 46 were obtained. They indicate 411.7 ± 8.4 Ma (n = 7; MSWD = 1.4), 512.3 ± 9.1 Ma (n = 16; MSWD = 1.1), 89.3 ± 2.7 Ma (n = 19; MSWD = 0.67), 101.2 ± 1.7 Ma (n = 46; MSWD = 0.42), 77.3 ± 4.1 Ma (n = 12; MSWD = 0.29), and 79.1 ± 4.8 Ma (n = 14; MSWD = 0.19), respectively. Granitoid samples from the Samarka Belt were RPM31, 32, and 45. They indicate 71.9 ± 2.5 Ma (n = 28; MSWD = 0.77), 91.7 ± 4.1 Ma (n = 6; MSWD = 1.05), and 105.7 ± 11.4 Ma (n = 6; MSWD = 0.15), respectively. Monazite ages of granitoid samples from the Taukha Belt, RPM51, 52, and 53 were also obtained. They indicate 83.1 ± 7.1 Ma (n = 6; MSWD = 0.16), 78.8 ± 9.0 Ma (n = 3; MSWD = 0.41), and 73.4 ± 2.9 Ma (n = 13; MSWD = 0.66), respectively. (Fig. 2)

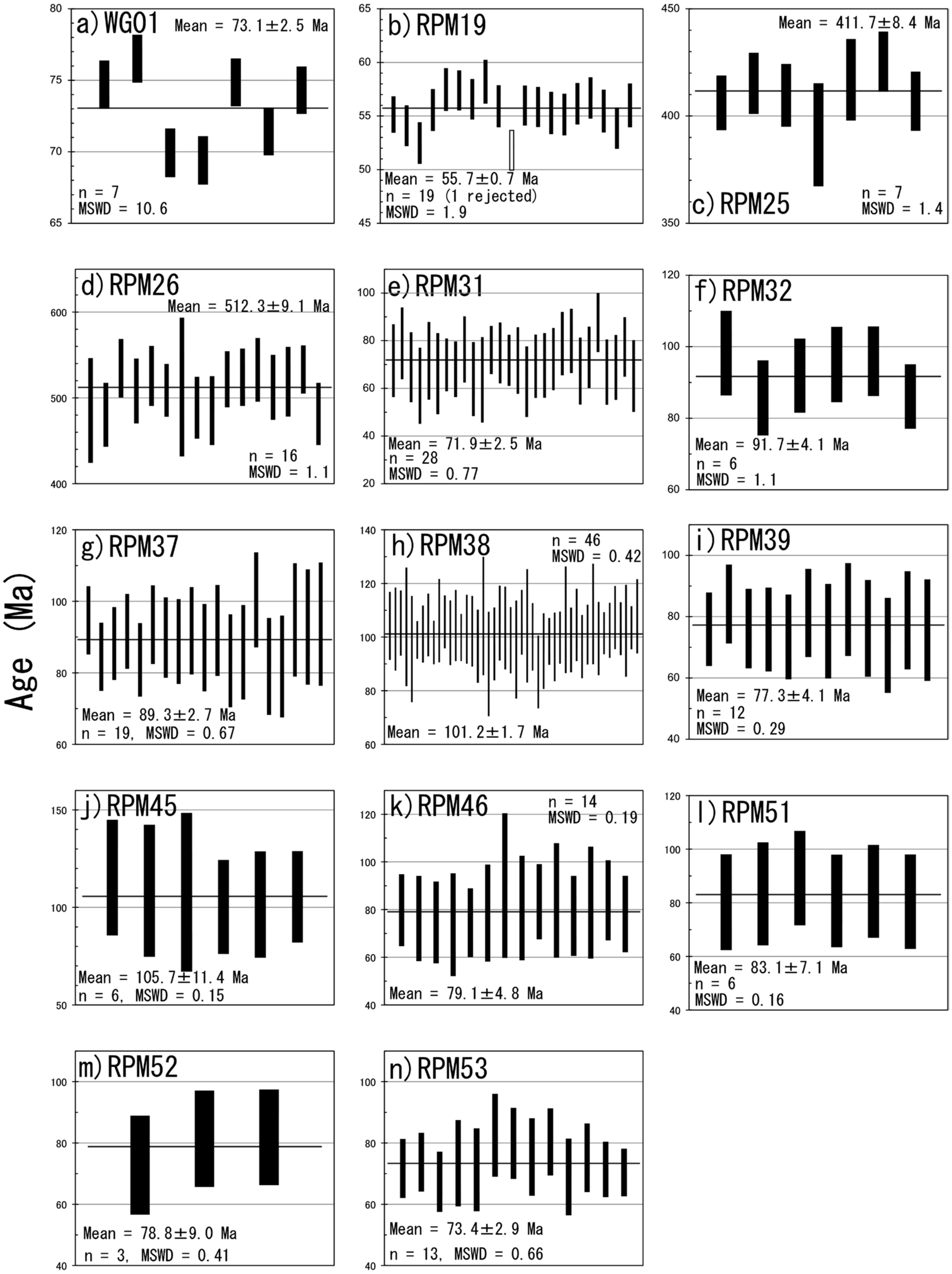

Fig. 2. Age distribution plots of U–Th–Pb chemical age. Error bars are 1σ. The uncertainties in the mean ages represent 95% confidence intervals.

U–Pb dating of zircon

The zircon grains for LA-ICP-MS analysis were handpicked from heavy fractions. Zircon grains from the samples, the zircon standard FC1 (^{206}Pb/^{238}U = 0.1859; Paces & Miller, 1993), and the glass standard NIST SRM610 were mounted in an epoxy resin and polished till the surface was flattened with the center of the embedded grains exposed. Both the backscattered electron and cathodoluminescence images were used to select the sites for analysis. U–Pb dating of these samples was carried out using an LA-ICP-MS that was assembled by NWR213 (Electro Scientific Industries) and Agilent 7700x (Agilent Technologies) that is installed at the National Museum of Nature and Science, Japan. The experimental conditions and the procedures followed for the measurements were based on Tsutsumi *et al*. (2012). The spot size of the laser was approximately 25 μm. A correction for common Pb was made on the basis of the measured ^{207}Pb (^{207}Pb correction) or ^{208}Pb and Th/U ratio (^{208}Pb correction) (e.g. Williams, 1998) and the model for common Pb compositions proposed by Stacey & Kramers (1975). The pooled ages presented in this study were calculated using Isoplot/Ex software (Ludwig, 2003). The uncertainties in the mean ^{238}U–^{206}Pb* ages represent 95% confidence intervals (95% conf.). ^{206}Pb* indicates radiometric ^{206}Pb.

We obtained zircon U–Pb mean ages from three rhyolite samples of RPM08, 12, and 18. They indicate 64.2 ± 2.8 Ma (n = 15; MSWD = 0.54), 60.0 ± 0.9 Ma (n = 17; MSWD = 2.4), and 55.0 ± 1.3 Ma (n = 16; MSWD = 1.9), respectively. Although, there is a possibility that RPM08 is excluded because of the error span, the rhyolite samples are thought to be Paleogene in age. Ages of three granitoid samples of RPM28, 29, and 34 are also obtained. Although the zircon ages are concentrated in one age, the samples RPM28 and 34 contain faintly older zircon grains than the cluster. The mean ages of the clusters indicate 472.4 ± 4.4 Ma (n = 22, 1 rejected; MSWD = 1.2), 88.1 ± 1.1 Ma (n = 32, 2 rejected; MSWD = 2.4), and 466.3 ± 5.3 Ma (n = 23, 2 rejected; MSWD = 2.0), respectively. (Fig. 3)

Discussion

As the Sea of Japan opened widely during the Early Miocene (Otofuji & Matsuda, 1983), one of the most important research subjects has been a geological correlation between the Japanese Islands and Primorye, Far East Russia, before the opening. A Sea of Japan coastal zone of the Japanese Islands is widely covered by Tertiary volcanics, the so-called Green-Tuff. On the other hand, Tertiary volcanics are poor along the coastal zone of Primorye, but pre-Tertiary rocks develop along the coast. Although pre-Tertiary rocks occur only sporadically along the coast of the Japanese Islands, some arrangement of the granitic rock and accretionary complex has been recognized in the Islands. Kojima *et al*. (2000) indicated a similarity between the Mino–Tanba accretionary complex in the Japanese Islands and the Samarka Belt in Primorye. Ishiwatari & Tsujimori (2003) found the correlation between the Hida Marginal Belt in Japan and Sergeevka belt in Primorye. This study will later allow for age comparison of igneous rocks between the Japanese Islands and Primorye.

In Primorye, it was thought that Early Cretaceous granitoids were widely distributed between two major faults: the Central Sikhote-Alin and Arseniev faults (e.g. Khanchuk *et al*., 1996). The samples of RPM29, 31, 32, and 45 are from the coastal part of the Samarka Belt, and RPM38, 39, 40, and 46 are from the Sergeevka Belt. They should belong to the Early Cretaceous granitoid region. However, except for RPM38 and 45, the ages of the samples are from 72 Ma to 92 Ma, and they are clearly Late Cretaceous in age. The age characteristics of granitoids in this region, which are Late Cretaceous and sporadically Early Cretaceous, are similar to the inner zone of southwest Japan (Yokoyama *et al*., 2016). Granitoids occurring along the coastal zone of the Sea of Japan in the Japanese Islands are less than 70 Ma, which is much younger than the Late Creta-

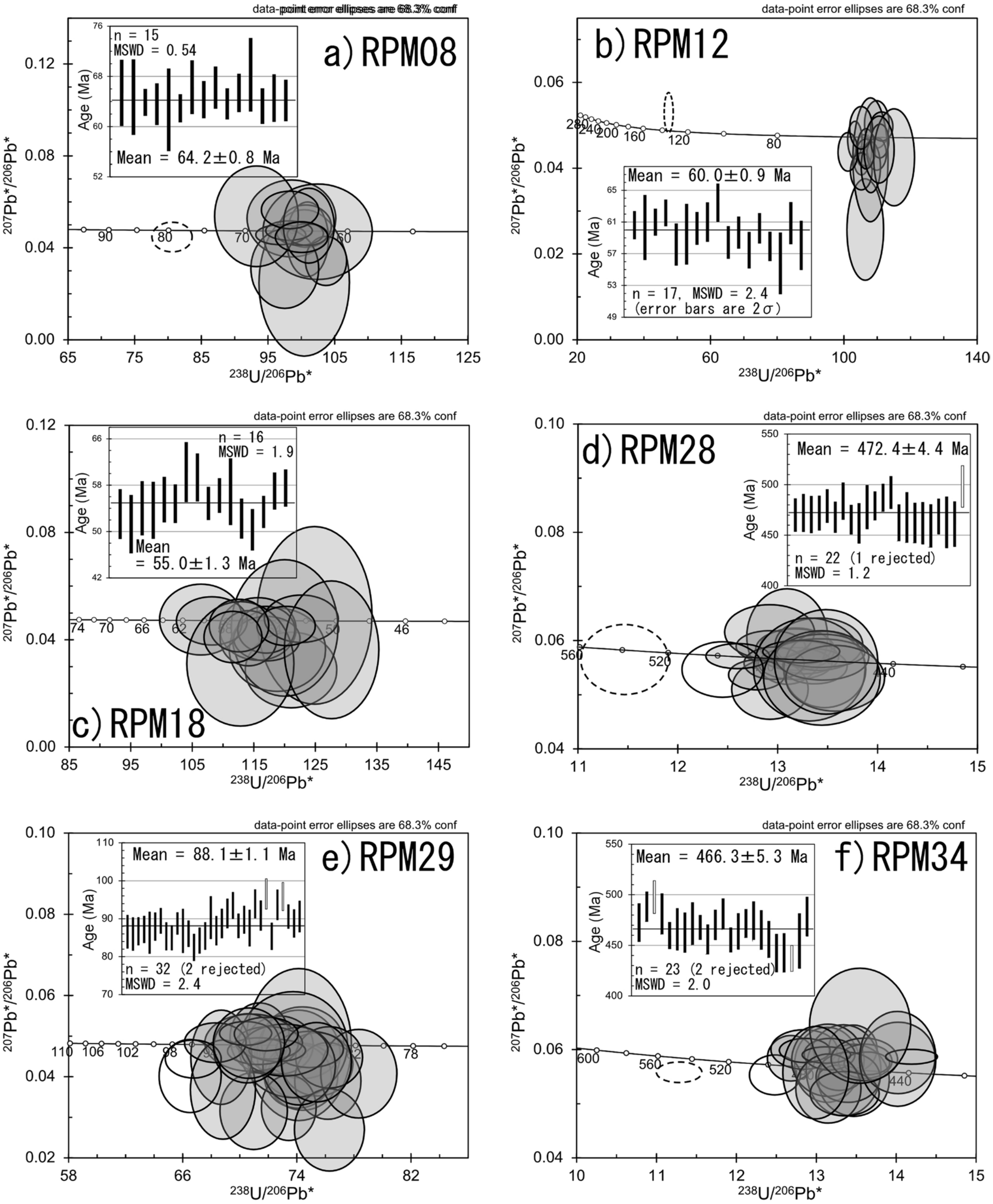

Fig. 3. Tera–Wasserburg U–Pb concordia diagrams and age distribution plot of zircon samples. The data on the concordia diagrams are corrected using ^{208}Pb correction and plotted with errors of 68.3% confidence intervals (1σ) whereas the data on the age distribution plots are corrected using ^{207}Pb correction and plotted with errors of 2σ. 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.

ceous granitoids in Primorye. As the Samarka Belt in Primorye is similar to the Mino-Tanba Belt in southwest Japan (Kojima *et al.*, 2000, 2001), the similarity of the granitoids in the Samarka Belt and the inner zone of the Japanese Islands does not conflict with the consanguineous relations between the Samarka Belt and the Mino–Tanba Belt.

On the other hand, the Taukha Belt corresponds to Jurassic to Early Cretaceous accretionary complexes in northeast Japan and the North Kitakami and Oshima belts (Kiminami *et al.*, 1992). But there is no age correlation of the intrusive rocks between northwest Japan and the Taukha Belt, which are 110–130 Ma and <90 Ma, respectively. The difference in the ages of the igneous rocks is probably due to the difference in the tectonic setting after the Jurassic to Early Cretaceous accretion.

Some granitoids analyzed in this study are over 400 Ma. They were found only in the western part of the Sergeevka Belt and are well consistent with the distribution of Paleozoic granitoids presented by Khanchuk *et al.* (1996). Including these older granitoids, we obtained reliable age data for igneous rocks in Primorye. Although it is inevitably necessary to obtain more age analyses for the comparison of igneous rocks in the Japanese Islands and Primorye, we hope that work in the near future of igneous ages in Primorye will present a more detailed geotectonic reconstruction model around the Sea of Japan.

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極東ロシア沿海州南部の火成岩の年代

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極東ロシア南部には大陸地塊の古生代の花崗岩の東側に，白亜紀以降の火成岩が分布している．日本海が形成される中新世以前は，極東ロシアと日本列島は地理的に近い位置にあったものと考えられ，極東ロシアの火成岩類と日本列島の火成岩類との間の連続性を確認するために，EPMAでモナズ石およびトール石，LA-ICP-MSでジルコンの年代測定を行なった．極東地域での火成岩の年代は，古い手法での年代が多く，十分に信頼できるデータが少なかった．今回の年代測定が今後の年代対比の一助になるものと考えている．