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한반도와 일본열도에서 일어난 페름기에서 쥐라기 화성작용에 대한 종합검토 및 지구조해석과 이를 이용한 고지리 재구성

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요 약

동아시아에는 고생대후기-쥐라기에 걸쳐 형성된 화강암류가 광범위하게 분포하고 있다. 이 논문에서는 한반도와 일본 열도에서 보고된 이들 화강암류에 대한 저어콘 U-Pb 연령자료를 검토하여 한반도와 일본열도에 나오는 페름기-쥐라기에 형성된 화강암류를 대비하고자한다. 페름기-쥐라기 화강암류들이 한반도 전역에 나타나지만 일본에서는 이들 화강암류들이 주로 히다 지역에 집중되어 나타나며 그 이외에 지역에서는 잘 나타나지 않는다. 한반도에서 280-215 Ma의 섭입 관련된 화성암류들은 주로 한반도 동남부에 속하는 경상분지, 영남육괴와 한반도 동북부에 속하는 관모육괴에 분포하는 반면 235-225 Ma의 충돌 후 환경에서 만들어진 화성암류는 경기육괴, 임진강대, 그리고 낭림육괴에 주로 나타난다. 한반도와 일본열도에 나타나는 섭입 관련 쥐라기 화강암류의 연령 분포는 화산호 전방 경계의 위치가 200-190 Ma에 트렌치 근처에 있었으며 170-160 Ma까지 점차 내륙으로 이동하였음을 지시한다. 이는 쥐라기 초 해양대지가 섭입하면서 발생된 부력에 의한 섭입 각도 감소에 기인한 것으로 생각된다. 180-160 Ma 시기의 화성암류가 한반도내에 광범위하게 나타남은 수평섭입이 일어났음을 지시한다. 히다벨트에는 260-230 Ma와 200-180 Ma에 섭입 관련 화성작용이 일어났으며 이는 히다벨트가 페름기-쥐라기에 한반도 동부해안에 형성된 대륙화산호에 위치하고 있었으며 아마도 한반도 남동부와 북동부에 형성된 대륙화산호 사이에 존재하였던 부분일 수 있다.

주요어: 한반도, 일본열도, 페름기-쥐라기, 화강암류, 저어콘 U-Pb 연령

Kenta Kawaguchi and Chang Whan Oh, 2021, A review of Permian to Jurassic magmatism along the Korean Peninsula and the Japanese Islands: Tectonic interpretations and a key for paleogeographic reconstructions. Journal of the Geological Society of Korea. v. 57, no. 4, p. 565-587

ABSTRACT: Late Paleozoic to Mesozoic granitoids occur extensively in East Asia. In this article, previously reported zircon U-Pb age data from the Korean Peninsula and the Japanese Islands are reviewed to examine the tectonic correlation of Permian to Jurassic granitoids between the Korean Peninsula and the Japanese Islands. Permian to Jurassic granitoids are widespread in the Korean Peninsula. In contrast, they are scarce in most parts of the Japanese Islands except the Hida Belt, Southwest Japan. The spatiotemporal distribution of the Permian to Jurassic granitoids in the Korean Peninsula shows the following pattern: ca. 280-215 Ma arc granitoids are found in the Gyeongsang Basin and Yeongnam Massif in the southeastern Korean Peninsula and in the Tumangang Belt, Kwanmo Massif, and Machollyong Belt in the northeastern Korean Peninsula, while ca. 235-225 Ma post-collisional granitoids occur mainly in the Gyeonggi Massif, Imjingang Belt, and Nangrim Massif. The distribution of the Jurassic arc-related granitoids in the Korean Peninsula and the Japanese Islands indicates the migration of the magmatic front from the trench side (ca. 200-190 Ma) to the inner continental side (ca. 170-160 Ma) due to the shallowing subduction angle. This was most likely induced by the buoyancy caused by the subduction of oceanic plateaus in the Early Jurassic, which are recognized in the Jurassic accretionary complex in Japan. Wide occurrence of later stage Jurassic magmatism (ca. 180-160 Ma) on the continental side of the Korean Peninsula indicates flat subduction. The arc igneous activity in the Hida Belt has two major phases of ca. 260-230 Ma and ca. 200-180 Ma, indicating that the Hida Belt may have been located in the continental arc that developed along the eastern margin of the Korean Peninsula from the Permian to Jurassic and may be a missing part between the continental arcs that developed in the southeastern and northeastern parts of the Korean Peninsula.

Key words: Korean Peninsula, Japanese Islands, Permian-Jurassic, granitoids, Zircon U-Pb age

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1. Introduction

The Korean Peninsula and the Japanese Islands occupy the eastern margin of the Asian continent. Opening of the East Sea (Japan Sea) in the Miocene (e.g., Otofuji, 1996 and references therein) separated the modern Japanese Islands from the Asian continent. Before the Miocene opening of the East Sea (Japan Sea), the Japanese Islands were formed along the eastern margin of the Asian continent. Revealing the tectonic linkages among the Asian continent, including the Korean Peninsula and the Japanese Islands, is extremely important to constrain the comprehensive evolutionary history of East Asia, especially during the Phanerozoic.

The tectonic correlations between the Korean Peninsula and the Japanese Islands have been debated for several decades by many authors (e.g., Otoh and Sasaki, 1998; Ishiwatari and Tsujimori, 2003; Oh, 2006); however, the validity of each model is still under debate. The basement rocks of the Korean Peninsula and the Japanese Islands are markedly different from each other. In particular, the Korean Peninsula mainly consists of continental affinity rock units that were formed since the Archean Eon, while the Japanese Islands contain continental- and/or island-arc affinity rock units that were mostly formed during the Phanerozoic Eon. Such differences cause limited occurrences of the correlatable rock units between them, which makes it difficult to obtain definitive correlations.

During the last several decades, a large amount of geochronological data has been produced due to the development of analytical techniques (equipment) such as thermal ionization mass spectrometry (TIMS), sensitive high-resolution ion microprobe (SHRIMP), and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). In addition, zircon U-Pb geochronology has become the most widely used tool for determining *in situ* ages with high precision (i.e., <±5%). Low- to medium-grade metamorphism does not reset zircon ages because of the high closure temperature of the zircon U-Pb system (>900℃; Cherniak and Watson, 2000). Therefore, zircon U-Pb ages obtained by the abovementioned equipment provide very important information regarding the crystallization age of zircons with high precision. However, some studies on the zircon U-Pb geochronology of the Korean Peninsula and the Japanese Islands have been published in local languages and are hardly accessible to the international community. From this point of view, it is necessary to review recent zircon U-Pb geochronological studies from the Korean Peninsula and the Japanese Islands written in English, Korean, and Japanese. In this review article, we review the ages of the Permian to Jurassic granitoids in the Korean Peninsula and the Japanese Islands, which could provide an important perspective to correlate the geology of Korea to that of Japan. Finally, we try to interpret the tectonic relationship between the igneous activities in the Korean Peninsula and the Japanese Islands during the Permian to Jurassic periods based on their spatiotemporal distribution from compiled zircon U-Pb ages in this review article.

2. General geology of the Korean Peninsula and the Japanese Islands

2.1 Korean Peninsula

The basement of the Korean Peninsula mainly consists of four Precambrian massifs: the Yeongnam, Gyeonggi, Nangrim, and Kwanmo Massifs from south to north (Fig. 1). These massifs under went polyphase tectono-thermal events during the Precambrian (e.g., Lee and Cho, 2012; Oh *et al.*, 2018). Three fold-thrust Belts separate these Precambrian massifs: the Neoproterozoic-Paleozoic Ogcheon Belt between the Yeongnam and Gyeonggi Massifs, the Paleozoic Imjingang Belt between the Gyeonggi and Nangrim Massifs, and the Neoarchean-Paleoproterozoic Machollyong Belt between the Nangrim and Kwanmo Massifs (Fig. 1). Cretaceous sedi-

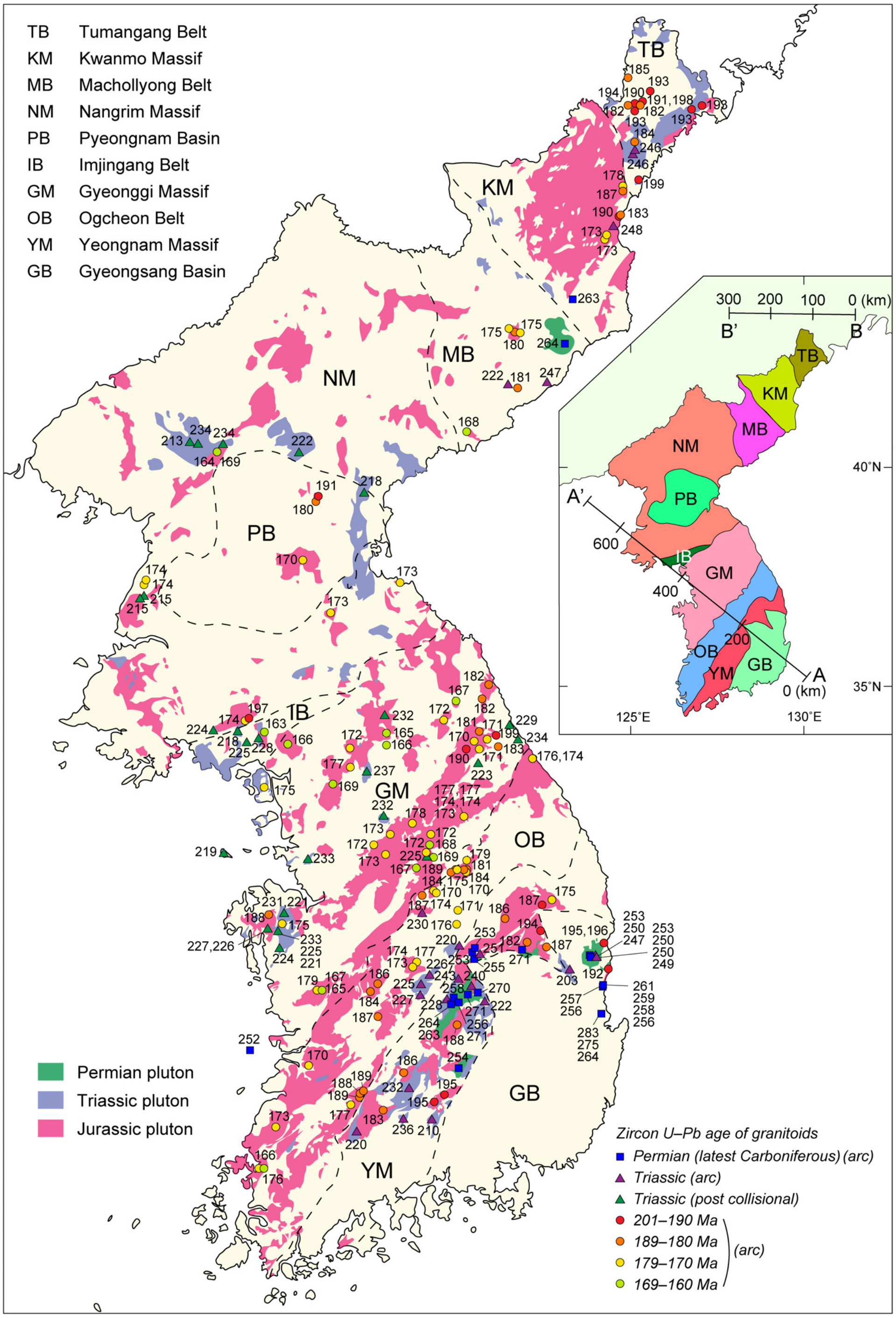

Fig. 1. Distribution of the Permian to Jurassic plutons in the Korean Peninsula after Kim, S.W. *et al*. (2021). The SHRIMP, TIMS, and LA-ICP-MS zircon U-Pb ages, locations, and the (probable) tectonic setting of the Permian to Jurassic granitoids are shown on this map. Data are after Wu *et al*. (2007), Park *et al*. (2010), Cheong and Kim (2012, and references therein), Yi *et al*. (2012), Yoon *et al*. (2014), Kim *et al*. (2015), Seo *et al*. (2016), Zhang *et al*. (2016), Zhai *et al*. (2016), Jo *et al*. (2018), Park *et al*. (2020), Choi *et al*. (2021), Kim, S.W. *et al*. (2021), and Zhang *et al*. (2021).

mentary and volcanic sequences of the Gyeongsang Basin are developed in the southeastern part of the Korean Peninsula and overlay the Yeongnam Massif (Fig. 1). The Kanmon and Toyonishi Groups in the northwestern part of Southwest Japan share common lithological features with the Gyeongsang Basin sequences (Ishiga *et al*., 1997; Lee *et al*., 2018). In the northeasternmost part of the Korean Peninsula, the late Paleozoic-Triassic Tumangang Belt formed within the Kwanmo Massif (Fig. 1). The Tumangang Belt is considered to be a different unit from the Precambrian Massifs and experienced subduction and collision (Jon *et al*., 2009; Zhang *et al*., 2016).

The eastern extent of the Dabie-Sulu collision Belt between the North China and South China Cratons into the Korean Peninsula has long been discussed. For example, the validity of the tectonic interpretation known as the Sino-Korean Craton model in which the basement massifs of the Korean Peninsula belong to the North China Craton has been supported by many authors (e.g., Zhai *et al*., 2007; Kim, M.J. *et al*., 2021). Yin and Nie (1993) suggested the indented model in which the Sulu collision Belt and Tanlu fault were considered to be correlated to the Imjingang Belt and Honam Shear Zone in the Korean Peninsula. In this model, the whole Gyeonggi Massif was considered to be correlated to the South China Craton. A model which considers the Hongseong-Imjingang Belt as a suture zone was also proposed (e.g., Kim, S.W. *et al*., 2011b). In this model, the western coast and other parts of the Gyeonggi Massif can be correlated to the North China and South China Cratons, respectively. On the other hand, Oh *et al*. (2005) suggested that the Dabie-Sulu collision Belt extends into the Gyeonggi Massif based on finding Permian-Triassic eclogite in the Hongseong area of the southwestern Gyeonggi Massif. Triassic post-collisional igneous rocks in the Odesan area of the eastern part of the Gyeonggi Massif further confirm that the Hongseong-Odesan Belt was the extension of the Dabie-Sulu collision Belt, which crosses the Gyeonggi Massif (Oh *et al*., 2006) and separates the Gyeonggi Massif into the Northern and Southern Gyeonggi Massifs (Oh and Kusky, 2007). In addition, Neoproterozoic igneous rocks in the Northern Gyeonggi Massif formed in a rift tectonic setting, whereas those of the Southern Gyeonggi Massif formed in both rift and arc tectonic environments (Lee *et al*., 2020). These characteristics support Oh and Kusky's tectonic model (2007), in which the Northern and Southern Gyeonggi Massifs were correlated with the North China and South China Cratons, respectively (Lee *et al*., 2020).

Numerous Phanerozoic plutonic rocks intruded throughout the whole Korean Peninsula. They occupy approximately one-third of the ground surface of the Korean Peninsula. Permian-Triassic granitoids in the southern part of the Korean Peninsula were mostly formed in a subduction-related tectonic setting, except for the Triassic post-collisional magmatic rocks in and around the Gyeonggi Massif (e.g., Kim, S.W. *et al*., 2011a; 2021; Kim, T.S. *et al*., 2011). These studies confirmed that the Korean Peninsula was affected by continental collisional events and subduction tectonism during the Permian to Triassic. The most abundant Jurassic Daebo granitoids are exposed throughout the Korean Peninsula as a product of arc magmatism (Fig. 1). The Cretaceous granitoids, so-called Bulguksa granitoids, occur mostly as small plutons and are mainly found in the Gyeongsang Basin. Igneous rocks showing the same intrusion age as those of the Bulguksa granitoids widely occur in the Japanese Islands.

2.2 Japanese Islands

In contrast to the Korean Peninsula, exposures of Precambrian outcrops are extremely limited on the Japanese Islands, and they occur only as small bodies with scales of less than several kilometers in two locations: the Oki Belt (Tsutsumi *et* al., 2006; Cho *et al*., 2021b; Kawabata *et al*., 2021) and the westernmost Maizuru Belt (Kimura *et al*., 2019, 2021).

Most of the basement rocks in the Japanese Islands consist of Phanerozoic subduction-related products such as accretionary complexes, high-pressure metamorphic complexes, ophiolites, and arc magmatic rocks (e.g., Ichikawa 1990; Wakita, 2013; Wallis *et al*., 2020). In Northeast Japan, a major part of the Paleozoic to Mesozoic basement rocks is covered by Cenozoic sediment and/or volcanic sequences, in contrast to their well exposure in Southwest Japan. In this respect, numerous studies on the pre-Cretaceous basement have been carried out in Southwest Japan to track tectonic evolution. Southwest Japan is further divided into the Inner Zone and Outer Zone by the Median Tectonic Line (MTL) (Fig. 2). The MTL marks a large geological contrast. The geotectonic units of the Inner Zone are characterized by accretionary complexes, high-pressure metamorphic rocks, ophiolites, and numerous Cretaceous to Paleogene igneous rocks, whereas those of the Outer Zone mostly consist of accretionary complexes and high-pressure metamorphic rocks without large Cretaceous to Paleogene igneous bodies.

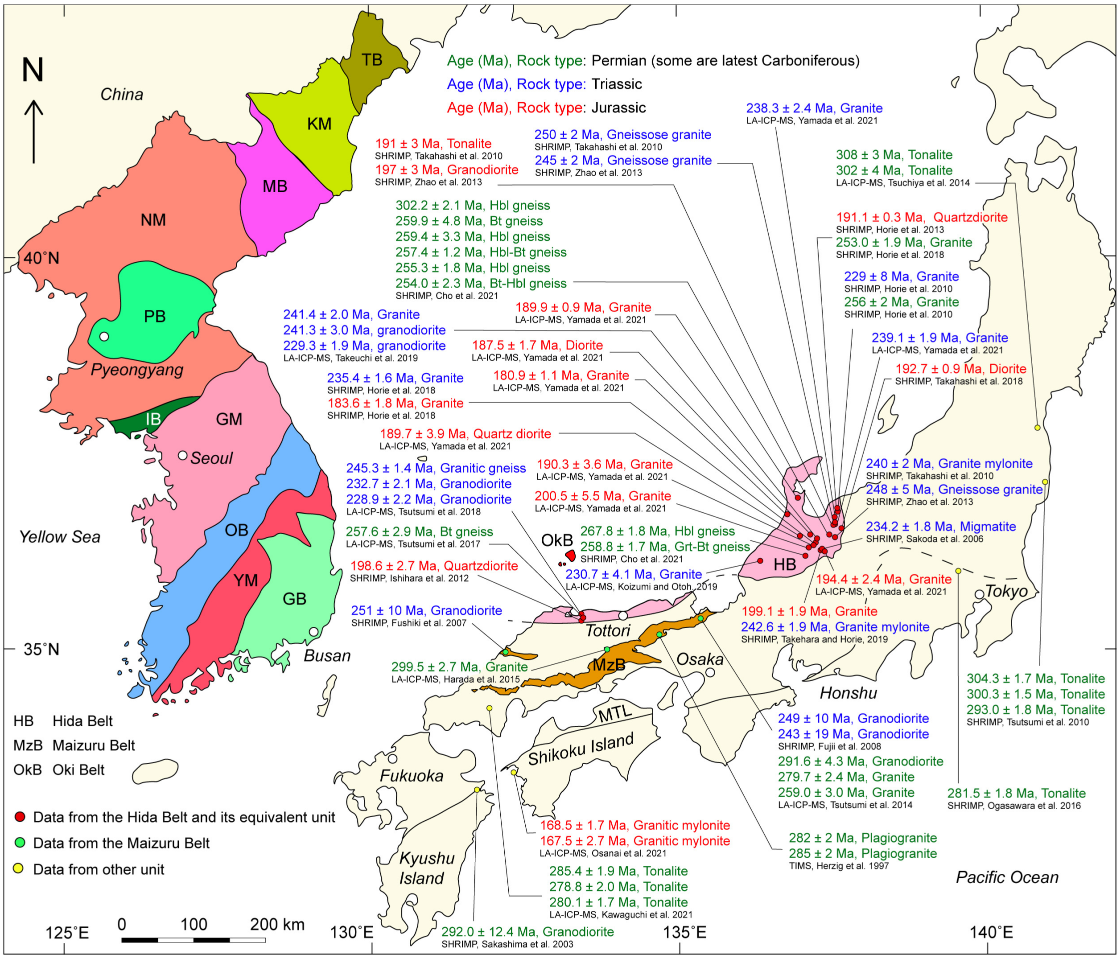

Fig. 2. Locations and zircon U-Pb ages of the Permian to Jurassic (partly latest Carboniferous) granitoids in the Japanese Islands from the previously reported literature. Data sources are same as compiled in Table 1. The distributions of the Hida Belt, Oki Belt, and Maizuru Belt are shown on this map.

In Southwest Japan, the major accretionary complexes are recognized as the Akiyoshi Belt (Permian), Ultra-Tamba Belt (Permian to Early Triassic), and Tamba-Mino-Ashio Belt (latest Triassic to earliest Cretaceous, mainly Jurassic) in the Inner Zone and the Chichibu Belt (Permian and Jurassic to earliest Cretaceous) and Shimanto Belt (Cretaceous to Paleogene) in the Outer Zone (brief summaries of these accretionary complexes are provided in Wakita (2013), Kojima *et al*. (2016) and Wallis *et al*. (2020)). High-pressure metamorphic complexes in the Inner Zone of Southwest Japan have been divided into three belts, the Renge/Sangun-Renge Belt (ca. 300 Ma), Suo Belt (ca. 220 Ma), and Chizu Belt (ca. 180 Ma), based on radiometric ages (Shibata and Nishimura, 1989). However, Nishimura (1998) reclassified the belts as the Renge Belt (330-280 Ma) and Suo Belt (230-160 Ma) based on integrated radiometric ages. Whether the two-division or three-division classification is applied still differs depending on the author. The Sambagawa/Sanbagawa Belt is developed in the Outer Zone of Southwest Japan. This Belt is characterized by Cretaceous high-pressure metamorphism (detailed geology is reviewed in Wallis and Okudaira, 2016). The Maizuru Belt in the Inner Zone of Southwest Japan (Fig. 2) is characterized as an island arc-back arc system that is different from the accretionary complexes and high-pressure metamorphic complexes in Southwest Japan. The Maizuru Belt is subdivided into the Southern, Central, and Northern zones based on lithology (Kano *et al*., 1959). The Southern, Central, and Northern zones are characterized as an intraoceanic island arc, back-arc basin, and continental crust, respectively (Kojima *et al*., 2016). Basically, the accretionary complexes and high-pressure metamorphic complexes of the Inner Zone mark a low-angle piled nappe structure and show a mosaic distribution pattern (Hayasaka, 1987). However, only the Maizuru Belt shows a remarkably linear distribution without showing a mosaic pattern. In addition, the Maizuru Belt crosscuts the zonal trend of the accretionary complexes and high-pressure metamorphic complexes. Moreover, the northern margin of the Maizuru Belt represents a high-angle dextral fault, whereas the southern boundary is characterized as a low-angle fault (Hayasaka, 1987). Although the tectonic evolution and setting of the Maizuru Belt are still under debate, a large-scale (i.e., 500 km) dextral strike-slip fault along the northern margin of the Maizuru Belt has been proposed to explain this pattern (Fujii *et al*., 2008).

Nearly 30% of the ground surface on the Japanese Islands is occupied by granitic rocks, and 80% of them formed during 130-40 Ma (e.g., Nakajima *et al*., 2016).

Outcrops of Precambrian rocks are found on Oki Island (the Oki Belt) and in the westernmost part of the Maizuru Belt, western Honshu Island (Fig. 2). The gneiss-granitoid complex on Oki Island is a Precambrian basement (Tsutsumi *et al*., 2006; Cho *et al*., 2021b; Kawabata *et al*., 2021), which may have been part of the continental massifs in the Korean Peninsula; however, details are still under debate. Another Archean to Paleoproterozoic magmatic-metamorphic complex named the "Tsuwano Complex" occurs as lenticular bodies less than 2.5 km in scale surrounded by the Permian sedimentary rocks of the Maizuru Belt (Kimura *et al*., 2019, 2021). Kimura *et al*. (2019, 2021) suggested the North China Craton as the origin of the Tsuwano Complex, which was transported as a result of the 500 km scale dextral strike-slip fault along the northern margin of the Maizuru Belt proposed by Fujii *et al*. (2008).

The Hida Belt, situated on the continental side of the Japanese Islands (Fig. 2), is characterized by Permian-Triassic and Jurassic granitoids (Hida granite), gneiss and migmatite (Hida gneiss), and intermediate pressure/temperature (P/T)-type schist (Unazuki schist). The lithological features of the Hida Belt mark a large contrast to other geotectonic units of the Japanese Islands. Therefore, the Hida

Belt has been considered to be a fragment of continental crust from a former East Asian continent. The Hida Belt is considered to be thrust upon the Hida Gaien Belt (also called the Hida Marginal Belt) and the Jurassic accretionary complex as a nappe, which is known as the "Hida Nappe" hypothesis (Komatsu *et al*., 1985). The Hida Nappe activity is thought to have occurred between 180 and 150 Ma because the Early Jurassic granitoids intruded into only the Hida Belt, while the Late Jurassic to Early Cretaceous sedimentary rocks cover both the Hida Belt and the surrounding units (Sohma and Kunugiza, 1993). The Hida Belt is characterized by the occurrence of a dextral ductile shear zone named the "Funatsu Shear Zone" (Komatsu *et al*., 1988). With recent progress in zircon U-Pb dating, the timing of mylonitization in the "Funatsu Shear Zone" is estimated to be between 243 and 191 Ma (Takahashi *et al*., 2010; Takehara and Horie, 2019) based on zircon U-Pb age dating from deformed and undeformed granitoids. Takahashi *et al*. (2010) further proposed that the dextral ductile shear activity of the "Funatsu Shear Zone" possibly took place ca. 215-211 Ma based on K-Ar dating of hornblende from fault-related rocks. Zhao *et al*. (2013) pointed out that the recrystallized zircon age of ca. 220 Ma from felsic gneiss possibly represents the timing of the Funatsu shear activity.

The paleoposition of the Hida Belt is still controversial, and different models have been proposed, such as the North China Craton origin (Horie *et al*., 2010, 2018; Takahashi *et al*., 2018), the South China Craton origin (Wallis *et al*., 2020), and the Central Asian Orogenic Belt (CAOB) origin (Zhao *et al*., 2013). Horie *et al*. (2010, 2018) revealed abundant Eoarchean to Paleoproterozoic inherited zircons from granitoids of the Hida Belt in the Unazuki area, and suggested that the source of the granitoids in the Unazuki area was the North China Craton based on older inherited zircons. On the other hand, Zhao *et al*. (2013) suggested that the origin of the Hida Belt was the Jiamushi Massif based on the similarity of the zircon U-Pb ages, lithological characteristics, and isotopic compositions.

3. Review of the Permian to Jurassic granitoids

The latest Paleozoic to Mesozoic granitoids are widespread in East Asia, including the Indochina Peninsula, southern to eastern parts of China, the Korean Peninsula, the Japanese Islands, and Far East Russia (e.g., Wakita *et al*., 2021). These granitoids are considered to have formed by subduction and/or collisional processes.

3.1 Korean Peninsula

The distributions of the Permian, Triassic, and Jurassic plutons in the Korean Peninsula are shown in Fig. 1 with zircon U-Pb ages and locations from previous studies.

Yi *et al*. (2012) reported the first zircon U-Pb ages from Permian arc-related plutons in South Korea (Fig. 1). Zircon U-Pb ages of 257.3 ± 2.0 and 255.7 ± 1.4 Ma from the Jangsari pluton and 252.9 ± 2.5 to 246.7 ± 2.1 Ma from the Yeongdeok pluton, located in the northeastern part of the Gyeongsang Basin, confirmed that the subduction system had developed since the Late Permian period (Yi *et al*., 2012). Kim, S.W. *et al*. (2021) reported Middle Permian to Late Triassic arc granitoids (271.5 ± 2.2 to 222.2 ± 0.5 Ma) from the central part of the Yeongnam Massif (Fig. 1). Based on their own results and previously reported data, Kim, S.W. *et al*. (2021) concluded that arc magmatism in the Yeongnam Massif initiated at least 272 Ma and continued until 216 Ma. Choi *et al*. (2021) further confirmed that the Permian arc-related magmatism in the Gyeongsang Basin can be traced back to 283.0 ± 1.8 Ma, and arc magmatism was long-lived (~30 Ma) in this region. Cheong *et al*. (2019) suggested that the ca. 222-217 Ma magmatism in the Yeongnam Massif formed under extension-related magmatism based on the integrated chronological, geochemical, and isotopic data of the plutons.

The Middle-Late Triassic plutonic rocks (ca. 235-225 Ma) found in and around the Gyeonggi Massif are considered to have formed in a post-collisional tectonic setting (e.g., Oh *et al.*, 2006; Williams *et al.*, 2009; Kim, S.W. *et al.*, 2011a; Kim, T.S. *et al.*, 2011; Cheong *et al.*, 2015, 2019; Fig. 1). The Triassic age peaks in the Gyeonggi Massif reflect considerable post-collisional igneous activity (Fig. 3d), while those of the Gyeongsang Basin, the Yeongnam Massif, and the Ogcheon Belt represent subduction-related arc magmatism (Fig. 3e, 3f). The Imjingang Belt and the Nangrim Massif have Triassic igneous rocks ranging from 234-215 Ma (Fig. 1). Although their tectonic setting is not entirely clear, these ages and geochemical characteristics are similar to those of the post-collisional igneous rocks in the Gyeonggi Massif (ca. 235-225 Ma; Fig. 1). Zhai *et al.* (2016) suggested that Triassic igneous activity in North Korea (mainly the Nangrim Massif) may have occurred in a postorogenic tectonic setting related to the collision between the North China and South China Cratons or the CAOB and North China Craton. Thus, the Triassic igneous rocks in the Nangrim Massif likely formed due to post-collisional activity, similar to the Gyeonggi Massif (Fig. 3c).

In the northeastern part of the Korean Peninsula, Middle Permian to Late Triassic igneous rocks occur related to 264-247 and 222 Ma igneous activity in the Machollyong Belt and the Kwanmo Massif and 248-246 Ma activity in the Tumangang Belt (Wu *et al.*, 2007; Zhai *et al.*, 2016, 2019; Zhang *et al.*, 2021; Figs. 1, 3a, 3b). Most of these ages are much older than the post-collisional activity in the Korean Peninsula and are probably not related to the collisional event. Instead, their age range is contemporaneous with the Permian to Triassic arc igneous rocks in the Gyeongsang Basin, Yeongnam Massif, and Ogcheon Belt. Zhang *et al.* (2016) pointed out that the Late Permian to Early

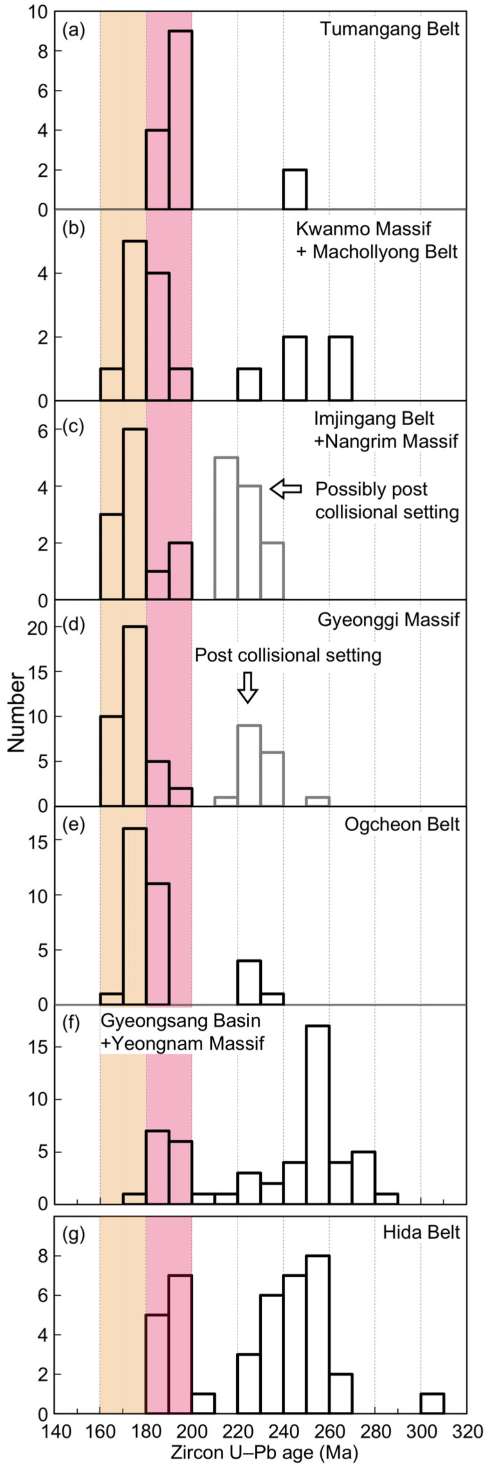

Fig. 3. Age histograms of the Permian-Jurassic (some are latest Carboniferous) granitoids in the Korean Peninsula from north to south (a-f) and the Hida Belt (g). The data sources are same as in Figs. 1 and 2.

Triassic granitoids in the northeastern part of the Korean Peninsula were most likely related to subduction-related magmatism.

Jurassic granitoids are widespread throughout the Korean Peninsula (Fig. 1) and are known as Daebo granitoids. Their ages show a range from ca. 200-160 Ma, with a magmatic hiatus of <160 Ma during the Late Jurassic Period. The spatio-temporal distribution of the Jurassic granitoids in the Korean Peninsula has long been discussed by many authors (e.g., Park *et al.*, 2010; Cheong and Kim, 2012; Kiminami and Imaoka, 2013; Kim *et al.*, 2015; Cheong and Jo, 2020; Lee *et al.*, 2021). Park *et al.* (2010) concluded that Jurassic igneous activity first occurred in the Yeongnam Massif at ca. 200 Ma; then, the locus of intrusion propagated further northwest until ca. 160 Ma. Park *et al.* (2010) explained this spatiotemporal distribution as reflecting variations in the distance to the trench, direction of subduction, and/or subduction angle. Kim *et al.* (2015) revealed the distribution of Jurassic granitoids based on SHRIMP zircon U-Pb dating of twenty-one samples from the southern Korean Peninsula: ca. 189-186 and 177 Ma from the northern margin of the southwestern Yeongnam Massif (the 177 Ma granitoid is located almost on the boundary with the Ogcheon Belt), ca. 178-166 Ma from the central Ogcheon Belt, ca. 176-174 Ma from the northeastern Ogcheon Belt, and ca. 177-173 Ma from the Gyeonggi Massif. Kim *et al.* (2015) further concluded based on integrated age data that Jurassic igneous activity gradually migrated toward the continental side across the Korean Peninsula as a result of the shallowing subduction angle of the paleo-Pacific plate. Cheong and Jo (2020) explained the migration of magmatic activity by the shallowing subduction angle and subsequent flat subduction possibly due to the subduction of buoyant material.

The Kwanmo Massif and Tumangang Belt of the northeastern part of the Korean Peninsula also have cohesive exposure of the Permian to Jurassic plutons, as mentioned above (Figs. 1, 3a, 3b). Although the available data are limited, Jurassic magmatic activity in this region shows an age range of ca. 198-173 Ma (Fig. 1), with a westward younging trend; igneous activities with ages of ca. 200-180 Ma occur in the Tumangang Belt (Fig. 3a), and those with ages of ca. 190-170 Ma are dominant in the Kwanmo Massif (Fig. 3b). Wu *et al.* (2007) suggested that the Jurassic igneous rocks in this region were possibly formed in an arc tectonic setting based on the occurrences of abundant subduction-related products along this area.

3.2 Japanese Islands

The Paleozoic to Jurassic granitoids are limited and localized in their distribution on the Japanese Islands. The locations and ages of the previously reported Permian to Jurassic (partly latest Carboniferous) granitoids based on zircon U-Pb dating are compiled in Fig. 2 and listed in Table 1. In this chapter, we review the Permian to Jurassic granitoids in the Hida Belt (3.2.1), Maizuru Belt (3.2.2), and other units (3.2.3) in the following subsections.

3.2.1 Permian to Jurassic granitoids in the Hida Belt

The magmatic activity in the Hida Belt took place during two major intervals: ca. 260-230 Ma (Hida older granite) and 200-180 Ma (Hida younger granite) (Horie *et al.*, 2010, 2013, 2018; Takahashi *et al.*, 2010, 2018; Zhao *et al.*, 2013; Koizumi and Otoh, 2019; Takehara and Horie, 2019; Takeuchi *et al.*, 2019; Cho *et al.*, 2021a; Yamada *et al.*, 2021; Figs. 2, 3g). Cho *et al.* (2021a) revealed the latest Carboniferous to Permian protolith magmatic ages of 302.2 ± 2.1, 267.8 ± 1.8, and 259.9 ± 4.8 to 254.0 ± 2.3 Ma from eight Hida orthogneiss samples and suggested that these ages represent arc igneous activity. Most recently, Yamada *et al.* (2021) confirmed that the activity of the Hida younger granite occurred until 180.9 ± 1.1 Ma. Arakawa

Table 1. Summary of the collected zircon U¬-Pb age data of Permian to Jurassic granitoids (partly latest Carboniferous) from the Japanese Islands. Abbreviation, Bt; biotite, Hbl; hornblende, Grt; garnet.

Sample No.	Rock type	Belt, Location, Province	Age (Ma)	± Error	Method	Reference	Remarks
Latest Carboniferous to Permian							
OT-272	Granite	Hida Belt, Unazuki, Central Honshu	256	± 2	SHRIMP	Horie *et al.* (2010)	
AB-6	Granite	Hida Belt, Unazuki, Central Honshu	253.0	± 1.9	SHRIMP	Horie *et al.* (2018)	
HD-7	Bt-Hbl gneiss	Hida Belt, Tateyama, Central Honshu	254.0	± 2.3	SHRIMP	Cho *et al.* (2021a)	*
HD-8	Hbl gneiss	Hida Belt, Tateyama, Central Honshu	255.3	± 1.8	SHRIMP	Cho *et al.* (2021a)	*
HD-9	Hbl-Bt gneiss	Hida Belt, Tateyama, Central Honshu	257.4	± 1.2	SHRIMP	Cho *et al.* (2021a)	*
HD-10	Hbl gneiss	Hida Belt, Tateyama, Central Honshu	302.2	± 2.1	SHRIMP	Cho *et al.* (2021a)	*
HD-12	Bt gneiss	Hida Belt, Tateyama, Central Honshu	259.9	± 4.8	SHRIMP	Cho *et al.* (2021a)	*
WR0504	Hbl gneiss	Hida Belt, Tateyama, Central Honshu	259.4	± 3.3	SHRIMP	Cho *et al.* (2021a)	*
HD-1	Hbl gneiss	Hida Belt, Tsunogawa, Central Honshu	267.8	± 1.8	SHRIMP	Cho *et al.* (2021a)	*
HD-6	Grt-Bt gneiss	Hida Belt, Tsunogawa, Central Honshu	258.8	± 1.7	SHRIMP	Cho *et al.* (2021a)	*
10MZ03	Bt gneiss	Unknown (Hida?), Tottori, Western Honshu	257.6	± 2.9	LA-ICP-MS	Tsutsumi *et al.* (2017)	*
MZ01	Granodiorite	Northern Maizuru Belt, Maizuru, Western Honshu	291.6	± 4.3	LA-ICP-MS	Tsutsumi *et al.* (2014)	
MZ06	Granite	Northern Maizuru Belt, Maizuru, Western Honshu	279.7	± 2.4	LA-ICP-MS	Tsutsumi *et al.* (2014)	
MG01	Granite	Northern Maizuru Belt, Maizuru, Western Honshu	259.0	± 3.0	LA-ICP-MS	Tsutsumi *et al.* (2014)	
KME-Gr4C	Granite	Northern Maizuru Belt, Okayama, Western Honshu	299.5	± 2.7	LA-ICP-MS	Harada *et al.* (2015)	**, ***
YO-1	Plagiogranite	Southern Maizuru Belt, Asago, Western Honshu	282	± 2	TIMS	Herzig *et al.* (1997)	
YO-2	Plagiogranite	Southern Maizuru Belt, Asago, Western Honshu	285	± 2	TIMS	Herzig *et al.* (1997)	
OTB-Gr1901	Tonalite	Suo Belt, Yamaguchi, Western Honshu	285.4	± 1.9	LA-ICP-MS	Kawaguchi *et al.* (2021)	
OTB-Gr2005	Tonalite	Suo Belt, Yamaguchi, Western Honshu	278.8	± 2.0	LA-ICP-MS	Kawaguchi *et al.* (2021)	
OTB-Gr1902	Tonalite	Suo Belt, Yamaguchi, Western Honshu	280.1	± 1.7	LA-ICP-MS	Kawaguchi *et al.* (2021)	
YR05	Tonalite	Unkwown, Kinshozan, Central Honshu	281.5	± 1.8	SHRIMP	Ogasawara *et al.* (2016)	
UG	Granodiorite	Unknown, Usukigawa, Eastern Kyushu	292.0	± 12.4	SHRIMP	Sakashima *et al.* (2003)	
GSJ-B326-b-1	Tonalite	Abukuma Belt, Fukushima, Northern Honshu	293.0	± 1.8	SHRIMP	Tsutsumi *et al.* (2010)	
GSJ-B326-b-6	Tonalite	Abukuma Belt, Fukushima, Northern Honshu	300.3	± 1.5	SHRIMP	Tsutsumi *et al.* (2010)	
GSJ-B326-b-8	Tonalite	Abukuma Belt, Fukushima, Northern Honshu	304.3	± 1.7	SHRIMP	Tsutsumi *et al.* (2010)	
KAKUDA7	Tonalite	Abukuma Belt, Miyagi, Northern Honshu	302	± 4	LA-ICP-MS	Tsuchiya *et al.* (2014)	
KAKUDA9	Tonalite	Abukuma Belt, Miyagi, Northern Honshu	308	± 3	LA-ICP-MS	Tsuchiya *et al.* (2014)	
Triassic							
1MAHI-1	Migmatite	Hida Belt, Kamioka, Central Honshu	234.2	± 1.8	SHRIMP	Sakoda *et al.* (2006)	
Ty208	Granite mylonite	Hida Belt, Tateyama, Central Honshu	240	± 2	SHRIMP	Takahashi *et al.* (2010)	
Ty136	Gneissose granite	Hida Belt, Tateyama, Central Honshu	250	± 2	SHRIMP	Takahashi *et al.* (2010)	
OT-52	Granite	Hida Belt, Unazuki, Central Honshu	229	± 8	SHRIMP	Horie *et al.* (2010)	

Table 1. Continued.

Sample No.	Rock type	Belt, Location, Province	Age ± Error (Ma)	Method	Reference	Remarks
07HI-4	Gneissose granite	Hida Belt, Tateyama, Central Honshu	248 ± 5	SHRIMP	Zhao *et al*. (2013)	
07HI-1	Gneissose granite	Hida Belt, Tateyama, Central Honshu	245 ± 2	SHRIMP	Zhao *et al*. (2013)	
KS090810-3	Granite	Hida Belt, Kagasawa, Central Honshu	235.4 ± 1.6	SHRIMP	Horie *et al*. (2018)	
KO-01	Granite mylonite	Hida Belt, Tateyama, Central Honshu	242.6 ± 1.9	SHRIMP	Takehara and Horie (2019)	
2901E	Granite	Hida Belt, Kagasawa, Central Honshu	241.4 ± 2.0	LA-ICP-MS	Takeuchi *et al*. (2019)	**
2901B	Granodiorite	Hida Belt, Kagasawa, Central Honshu	241.3 ± 3.0	LA-ICP-MS	Takeuchi *et al*. (2019)	**
1203D	Granodiorite	Hida Belt, Kagasawa, Central Honshu	229.3 ± 1.9	LA-ICP-MS	Takeuchi *et al*. (2019)	**
KAD02	Granite	Hida Belt, Katsuyama, Central Honshu	230.7 ± 4.1	LA-ICP-MS	Koizumi and Otoh (2019)	**
HD07	Mylonitized granite	Hida Belt, Katakaigawa, Central Honshu	238.3 ± 2.4	LA-ICP-MS	Yamada *et al*. (2021)	
HD10	Mylonitized granite	Hida Belt, Katakaigawa, Central Honshu	239.1 ± 1.9	LA-ICP-MS	Yamada *et al*. (2021)	
IY1	Deformed granodiorite	Unknown (Hida?), Tottori, Western Honshu	228.9 ± 2.2	LA-ICP-MS	Tsutsumi *et al*. (2018)	**, ***
IY3-2	Granitic gneiss	Unknown (Hida?), Tottori, Western Honshu	245.3 ± 1.4	LA-ICP-MS	Tsutsumi *et al*. (2018)	**, ***
IY4-1	Deformed granodiorite	Unknown (Hida?), Tottori, Western Honshu	232.7 ± 2.1	LA-ICP-MS	Tsutsumi *et al*. (2018)	**, ***
No name	Granodiorite	Maizuru Belt, Gotsu, Western Honshu	251 ± 10	SHRIMP	Fushiki *et al*. (2007)	**, ***
MZ-2	Granodiorite	Northern Maizuru Belt, Maizuru, Western Honshu	249 ± 10	SHRIMP	Fujii *et al*. (2008)	
MZ-3	Granodiorite	Northern Maizuru Belt, Maizuru, Western Honshu	243 ± 19	SHRIMP	Fujii *et al*. (2008)	
Jurassic						
OT04	Quartzdiorite	Hida Belt, Unazuki, Central Honshu	191.1 ± 0.3	SHRIMP	Horie *et al*. (2013)	
KS090810-1	Granite	Hida Belt, Kagasawa, Central Honshu	183.6 ± 1.8	SHRIMP	Horie *et al*. (2018)	
KO-03	Granite	Hida Belt, Tateyama, Central Honshu	199.1 ± 1.9	SHRIMP	Takehara and Horie (2019)	
TY008	Diorite	Hida Belt, Tateyama, Central Honshu	192.7 ± 0.9	SHRIMP	Takahashi *et al*. (2018)	
Ty124	Tonalite	Hida Belt, Tateyama, Central Honshu	191 ± 3	SHRIMP	Takahashi *et al*. (2010)	
07HI-2	Granodiorite	Hida Belt, Tateyama, Central Honshu	197 ± 3	SHRIMP	Zhao *et al*. (2013)	
HD17	Granite	Hida Belt, Funatsu, Central Honshu	194.4 ± 2.4	LA-ICP-MS	Yamada *et al*. (2021)	
HD26	Granite	Hida Belt, Moriyasu, Central Honshu	200.5 ± 5.5	LA-ICP-MS	Yamada *et al*. (2021)	
HD28	Granite	Hida Belt, Utsubo, Central Honshu	190.3 ± 3.6	LA-ICP-MS	Yamada *et al*. (2021)	
HD37m	Quartz diorite	Hida Belt, Shokawa, Central Honshu	189.7 ± 3.9	LA-ICP-MS	Yamada *et al*. (2021)	
HD38	Diorite	Hida Belt, Yatsuo, Central Honshu	187.5 ± 1.7	LA-ICP-MS	Yamada *et al*. (2021)	
HD39	Granite	Hida Belt, Hodatsusan, Central Honshu	180.9 ± 1.1	LA-ICP-MS	Yamada *et al*. (2021)	
HD43	Granite	Hida Belt, Sekidosan, Central Honshu	189.9 ± 0.9	LA-ICP-MS	Yamada *et al*. (2021)	
No. 2305	Quartzdiorite	Ebi Granite (Hida?), Tottori, Western Honshu	198.6 ± 2.7	SHRIMP	Ishihara *et al*. (2012)	**
50305F	Granitic mylonite	Oshima metamorphic complex, Ehime, Western Shikoku	168.5 ± 1.7	LA-ICP-MS	Osanai *et al*. (2021)	**
61202A	Granitic mylonite	Oshima metamorphic complex, Ehime, Western Shikoku	167.5 ± 2.7	LA-ICP-MS	Osanai *et al*. (2021)	**

*Protolith age, **In Japanese, ***Abstract and Shinmura (1995) revealed that the Hida granitoids (including both the Hida older and Hida younger granites) show an arc tectonic setting based on whole-rock chemical analysis. Horie *et al*. (2010) also suggested that most Hida granitoids formed in an arc tectonic setting except for one analyzed sample (256 ± 2 Ma granite) that shows transitional features between the arc and syn-collisional granite fields; however, more studies are needed, as suggested by Horie *et al*. (2010). Most recently, Yamada *et al*. (2021) confirmed that both the Triassic (Hida older granite) and Jurassic (Hida younger granites) plutons show subduction-related characteristics, such as negative Nb and Ta anomalies, and display an arc tectonic setting based on whole-rock geochemical data. Based on these previously reported data, granitoids in the Hida Belt are considered to have formed during two prominent magmatic episodes ca. 260-230 and 200 -180 Ma (Figs. 2, 3g) in an arc tectonic setting.

Apart from the main distribution area within the Hida Belt in central Honshu, the western part of the Tottori area in western Honshu also has Permian to Jurassic granitoids (Fig. 2; Table 1). Although their affinities are still under debate, this paper considers these rocks as part of the Hida Belt following the interpretation of Ishiga *et al*. (1989) and Tsutsumi *et al*. (2018). Previously, Ishiga *et al*. (1989) suggested that the Hida Belt extends to the western Tottori area based on the findings of gneisses and mylonites. The Jurassic granitoids (198.6 ± 2.7 Ma from quartz diorite; Ishihara *et al*., 2012; Fig. 2; Table 1) in this area are in contact with the Mesozoic high-pressure metamorphic rocks to the south, and this boundary is defined as the "Ebi Tectonic Zone" (Ishiga *et al*., 1991). The tectonic features of this boundary are very important because they indicate that the rock unit (Hida Belt equivalent) of which the continental affinity is in contact with that (Mesozoic high-pressure metamorphic complex) of the accretionary affinity. Further study is necessary to reveal the details of the Ebi Tectonic Zone, which possibly holds a key to correlating the Korean Peninsula and the Japanese Islands.

3.2.2 Permian to Triassic granitoids in the Maizuru Belt

Permian to Triassic granitoids in the Maizuru Belt can be divided into two types based on their petrological and lithological characteristics. One is found in the Northern Maizuru Belt, and the other occurs in the Southern Maizuru Belt. Granitoids are a major lithological phase in the Northern Maizuru Belt and show a wide age range from the Archean-Paleoproterozoic and Cambrian to Triassic (ca. 2700, 2500, 1850 Ma, and 489-243 Ma; Fujii *et al*., 2008; Tsutsumi *et al*., 2014; Harada *et al*., 2015; Kimura *et al*., 2019, 2021). Granitoids in the Northern Maizuru Belt are correlated with East Asian blocks, such as the Khanka Massif (Fujii *et al*., 2008; Tsutsumi *et al*., 2014) and North China Craton (Kimura *et al*., 2019, 2021), based mainly on their similar ages. In contrast to the Northern Maizuru Belt, in the Southern Maizuru Belt, gabbroic rocks known as the Yakuno ophiolite are the major phase with minor granitoids (Ishiwatari, 1985, 1999; Suda *et al*., 2014; Suda and Hayasaka, 2009). From the Southern Maizuru Belt, only Early Permian zircon U-Pb ages (285 ± 2 and 282 ± 2 Ma from the plagiogranite) have been reported thus far (Herzig *et al*., 1997; Fig. 2; Table 1). Moreover, the Early Permian granitoids in the Southern Maizuru Belt are considered to have formed in an intraoceanic island arc setting based on their petrological and geochemical characteristics (Suda *et al*., 2014).

3.2.3 Permian and Jurassic granitoids in other units

Extremely small and isolated exposures of Permian granitoids have been reported with ages of 290.0 ± 12.4 Ma (Sakashima *et al*., 2003) from easternmost Kyushu, 285.4 ± 1.9 to 278.8 ± 2.0 Ma (Kawaguchi *et al*., 2021) from western Honshu, 285.1 ± 1.8 Ma (Ogasawara *et al*., 2016) from central Honshu and

304.3 ± 1.7 to 293.0 ± 1.8 Ma (Tsutsumi *et al.*, 2010) and 308 ± 3 to 302 ± 4 Ma (Tsuchiya *et al.*, 2014) from Northeast Japan (Fig. 2, Table 1). However, they occur as small bodies, and the detailed tectonic linkages between them and the surrounding tectonic units and their origin are still unknown.

Jurassic granitoids also occur on the westernmost part of Shikoku Island in the Outer Zone of Southwest Japan as small, elongated mylonitic bodies less than 100 m in scale (Fig. 2; Table 1). The granitic mylonites show ages of 168.5 ± 1.7 and 167.5 ± 2.7 Ma (Osanai *et al.*, 2021). This body does not affect the surrounding rocks through contact metamorphism, and their boundary is marked as a fault (Takeda, 1995; Osanai *et al.*, 2021). Therefore, this rock body likely occurs as exotic blocks, and no tectonic model regarding the origin of these granitoids has been proposed thus far.

4. Tectonic implications

4.1 Magmatic front migration during the Jurassic

Although Permian to Jurassic plutons are widespread throughout the Korean Peninsula, their distribution has a definitive trend. To reveal the spatiotemporal distribution of the Permian to Jurassic plutons in the Korean Peninsula, we projected the zircon U-Pb ages of granitoids along the SE-NW-directed A-A′ line (Fig. 4a) and E-W-directed B-B′ line (Fig. 4b), as shown in Fig. 1. The Permian to

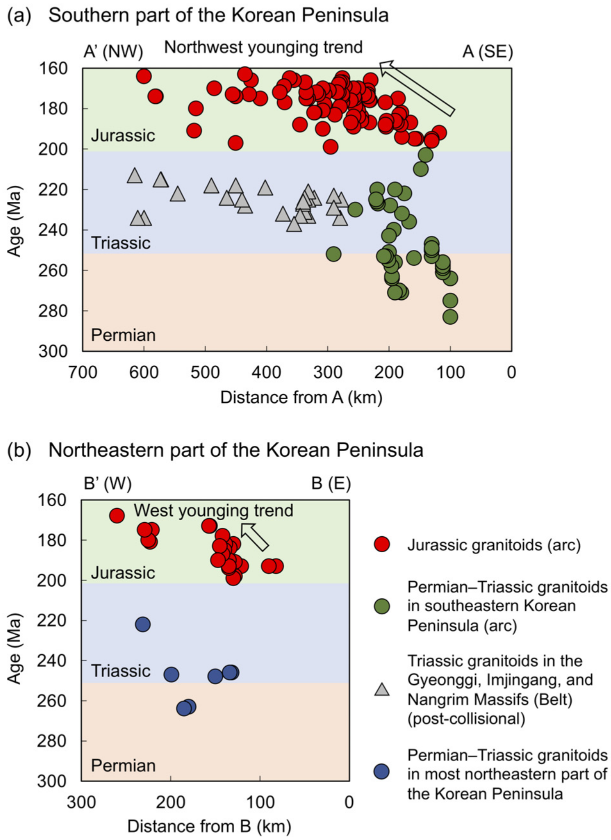

Fig. 4. (a) Projection of the zircon U-Pb ages from the granitoids in the southern part of the Korean Peninsula (the Gyeongsang Basin, Yeongnam Massif, Ogcheon Belt, Gyeonggi Massif, Imjingang Belt, and Nangrim Massif) to the SE-NW oriented A-A’ line shown in Fig. 1. (b) Projection of the zircon U-Pb ages from the granitoids in the northeastern part of the Korean Peninsula (the Tumangang Belt, Kwanmo Massif, and Machollyong Belt) to the E-W oriented B-B’ line displayed in Fig. 1.

Triassic arc-related granitoids exposed in the southeastern part of the Korean Peninsula (the Yeongnam Massif and Gyeongsang Basin; Figs. 3f, 4a) do not show any clear trend. This pattern indicates the existence of prolonged arc magmatic activity in this region starting in the late Early Permian (Fig. 4a). However, a lull in arc magmatic activity probably occurred in the Late Triassic (after ca. 216 Ma; Figs. 3f, 4a). The Middle to early-Late Triassic post-collisional granitoids in Fig. 4a mostly correspond to the magmatism in the Gyeonggi Massif, Imjingang Belt, and Nangrim Massif. The Triassic igneous rocks in the central to western part of the Nangrim Massif are slightly younger than those in the Gyeonggi Massif, Imjingang Belt, and southern margin of the Nangrim Massif; however, they may have formed in a post-collisional setting (Figs. 1, 3c). The Permian to Triassic granitoids in the northeastern part of the Korean Peninsula (Fig. 4b) are considered to be related to arc igneous activity (Fig. 4b).

The magmatism of the Jurassic granitoids in the Gyeongsang Basin and Yeongnam Massif occurred mostly during ca. 200-180 Ma (Fig. 3f). The ages of magmatic activity in the Ogcheon Belt (ca. 190-170 Ma) are younger than those in the Gyeongsang Basin and Yeongnam Massif (Fig. 3e). Moreover, the ages of the main Jurassic magmatic activity in the Gyeonggi and Nangrim Massifs and Imjingang Belt are much younger, ca. 180-160 Ma (Fig. 3c, 3d). Although the number of data points is limited, the Tumangang Belt in the northeasternmost part of the Korean Peninsula shows a magmatic age of ca. 200-180 Ma, which is the same as those of the Gyeongsang Basin and Yeongnam Massif in the southeastern part of the Korean Peninsula (Fig. 3a, 3f). The ages of igneous activity in the Kwanmo Massif and Machollyong Belt located to the southwest of the Tumangang Belt are much younger than those in the Tumangang Belt (mostly 190-170 Ma) and are similar to those in the Ogcheon Belt (Fig. 3a, 3b). On the Korean Peninsula, Jurassic magmatic activity stopped ca. 160 Ma (Fig. 3a-f). These Jurassic plutons in the Korean Peninsula are thought to have formed in an arc tectonic setting (e.g., Kim *et al*., 2015). In contrast to the Permian to Triassic arc-related granitoids, Jurassic granitoids show a wide distribution with a northwestward younging trend in the southern parts of the Korean Peninsula (Fig. 4a) and a westward younging trend in the northeastern part (Fig. 4b). In summary, the Jurassic magmatic trend in the Korean Peninsula during the early stage of Jurassic magmatism (ca. 200-190 Ma) indicates that subduction-related igneous activity took place on the trench side (Fig. 5a). At the same time, the Jurassic accretionary complex of the Tamba-Mino-Ashio Belt formed in the nonmagmatic forearc region (Fig. 5a). As subduction progressed, the magmatic front propagated toward the interior of the continent (Fig. 5b) because the dehydration position of the subducted oceanic crust migrated inland due to the shallowing subduction angle (Fig. 5).

The subduction angle shallowing was most likely induced by the subduction of buoyant materials such as ridges or oceanic plateaus. Studies of the Jurassic accretionary complex in the Inner Zone of Southwest Japan hold a key clue to confirm this possibility. During the Jurassic, voluminous accretionary complexes were formed in the forearc region, which are presently recognized as the Tamba-Mino-Ashio Belt in Southwest Japan (Fig. 5). Pelagic radiolarian chert is extremely abundant in the Tamba-Mino-Ashio Belt (Matsuda and Isozaki, 1991; Nakae, 2000). This lithological feature indicates that the subducted oceanic crust was quite old and cold. Therefore, ridge subduction is unlikely to have occurred. Instead, accreted mafic rock of the Tamba-Mino-Ashio Belt indicates a hot spot oceanic island and/or oceanic plateau setting (Jones *et al*., 1993; Koizumi and Ishiwatari, 2006; Ichiyama *et al*., 2008). Moreover, fragments of Carboniferous to Early Permian oceanic plateaus have been reported from the Early Jurassic accretionary complex (Type II unit of the Tamba Belt, western Honshu) (Koizumi and Ishiwatari, 2006). Therefore, the oceanic plateaus were subducted under the trench during the Early Jurassic (Fig. 5a, 5b). Subduction of thick oceanic plateaus caused shallow subduction due to their higher buoyancy than thin mid-ocean ridge basalt (MORB)-type oceanic crust. Continuous subduction of the oceanic plateaus caused further shallowing of the

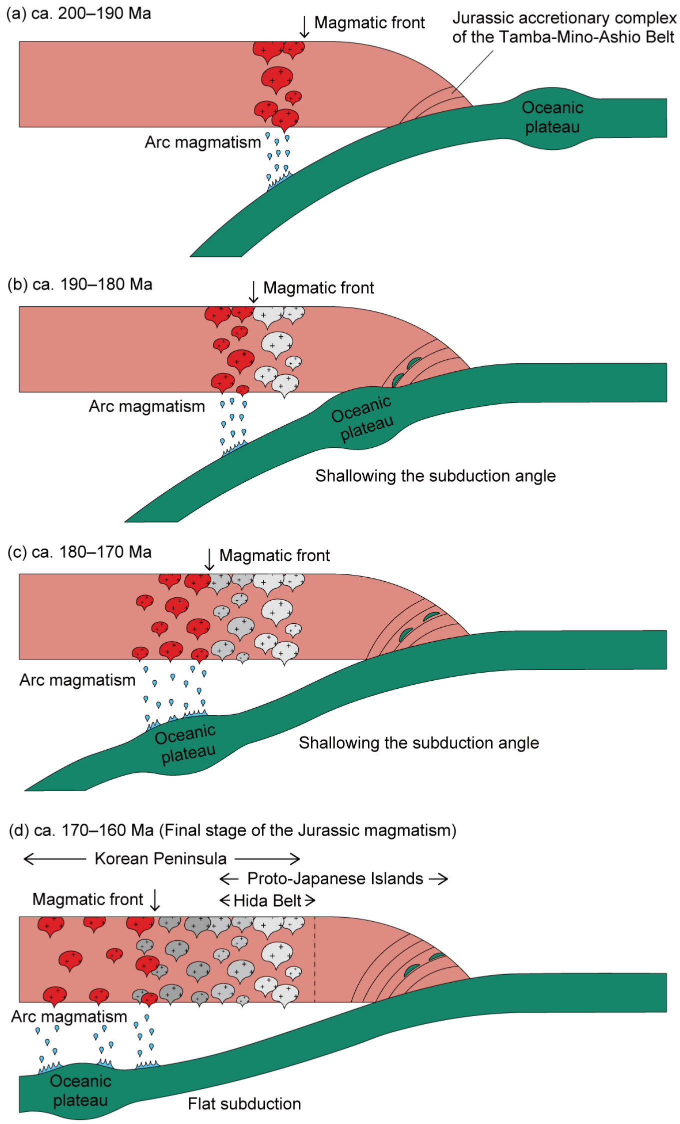

Fig. 5. Schematic illustration of the spatiotemporal distribution of the Jurassic plutons along the Korean Peninsula to the proto-Japanese Islands. (a) The Jurassic subduction system initiated ca. 200 Ma, forming arc magmatic rocks and the Jurassic accretionary complex of the Tamba-Mino-Ashio Belt in the Inner Zone of Southwest Japan. (b) The 190-180 Ma magmatic front migrated inland due to the shallowing subduction angle, probably caused by the subduction of buoyant oceanic plateaus. (c) The 180-170 Ma magmatic front propagated toward the continental side, and the granitoids during this period show a wide distribution with the progress of the subduction of the oceanic plateaus. (d) Flat subduction due to the subduction of oceanic plateaus formed wide occurrences of arc magmatism during ca. 170-160 Ma.

subduction angle, and the magmatic front propagated inland during ca. 180-170 Ma (Fig. 5c). In addition, younger Jurassic magmatic activity (ca. 180-160 Ma) occurred widely in the central to western part of the Korean Peninsula (Figs. 1, 5c, 5d). This is most likely due to flat subduction resulting from the continuous shallowing of the subduction angle (Fig. 5c, 5d).

In addition to the southern part of the Korean Peninsula, the Jurassic magmatic rocks of the northeastern part of the peninsula display a westward younging trend (Fig. 4b). This distribution indicates that the westward migration of the arc front occurred in the northeastern part of the Korean Peninsula during this time, probably due to the shallowing subduction angle of the paleo-Pacific plate, as in the southern part of the Korean Peninsula.

Based on the spatiotemporal distribution of the Jurassic granitoids in the Korean Peninsula, estimated magmatic fronts at 190 Ma, 180 Ma, and 170 Ma are displayed in Fig. 6. During the early stage of the Jurassic Period ca. 200-190 Ma, subduction-related arc igneous activity took place in the southeastern and northeastern parts of the modern Korean Peninsula and might have marked a NE-SW- to N-S-trending arc belt (Fig. 6). The magmatic front moved continuously toward the interior of the continent from 200 to 170 Ma along the NE-SW- to N-S-trending arc belt (Fig. 6). The wide distribution of later-stage Jurassic granitoids (ca. 180-160 Ma) in the central to western Korean Peninsula indicates that arc igneous activities were abundant on the continental side far from the trench. This distribution can be explained by the flat subduction of the paleo-Pacific plate, as mentioned above (Fig. 5d).

4.2 Paleogeographical position of the Hida Belt

In the Hida Belt, the Jurassic granitoids show an age range of 201-181 Ma (Horie *et al*., 2010, 2013, 2018; Takahashi *et al*., 2010, 2018; Zhao *et al*., 2013; Takehara and Horie, 2019; Cho *et al*., 2021a; Yamada *et al*., 2021; Figs. 2, 3; Table 1) and formed in an arc tectonic setting (Arakawa and Shinmura, 1995; Horie *et al*., 2010; Yamada *et al*., 2021). Therefore, the Hida Belt was located on the trench side of the magmatic front along the Korean Peninsula during ca. 200-180 Ma (Figs. 5d, 6). After the active arc magmatism ca. 200-180 Ma, the Hida Belt probably moved toward the trench and then structurally thrusted upwards on the Hida Gaien Belt and the accretionary complexes of Southwest Japan, resulting in the Hida Nappe movement (Komatsu *et al*., 1985) during ca. 180-150 Ma (Sohma and Kunugiza, 1993) (Fig. 6).

Although the Northern Maizuru Belt has Permian to Triassic granitoids as well as Archean-Paleoproterozoic and Paleozoic granitoids, they are located inside the Japanese accretionary units (Fig. 2). These bodies can be considered exotic blocks derived from former East Asian blocks such as the Khanka Massif and/or the North China Craton as a result of the dextral strike-slip fault along the northern margin of the Maizuru Belt (Fujii *et al*., 2008).

4.3 Paleogeography of the Permian arc along the Korean Peninsula

Permian detrital zircon grains with peak ages of ca. 280-250 Ma are abundant in the (meta-) sedimentary rocks in the Middle Permian to Late Triassic accretionary complexes and the high-pressure metamorphic complexes in the Inner Zone of Southwest Japan, such as Akiyoshi and Suo Belts (e.g., Tsutsumi *et al*., 2000; Zhang *et al*., 2018a, 2018b; Kawaguchi *et al*., 2021). In addition, Wakita *et al*. (2021) clearly showed an abundant ca. 270-240 Ma detrital zircon population from the Permian to Cretaceous accretionary complexes in Japan. These data indicate that the Permian magmatic rocks played an important role in supplying zircon grains to the Permian-Triassic trench along proto-Japan. Considering the occurrences of Permian arc magmatic rocks in the Gyeongsang Basin, Yeongnam Massif, and northeastern part of the

Korean Peninsula (Fig. 1), the Permian magmatic arc probably existed along the southeastern and northeastern parts of the Korean Peninsula. However, it is still unclear whether these arc belts were

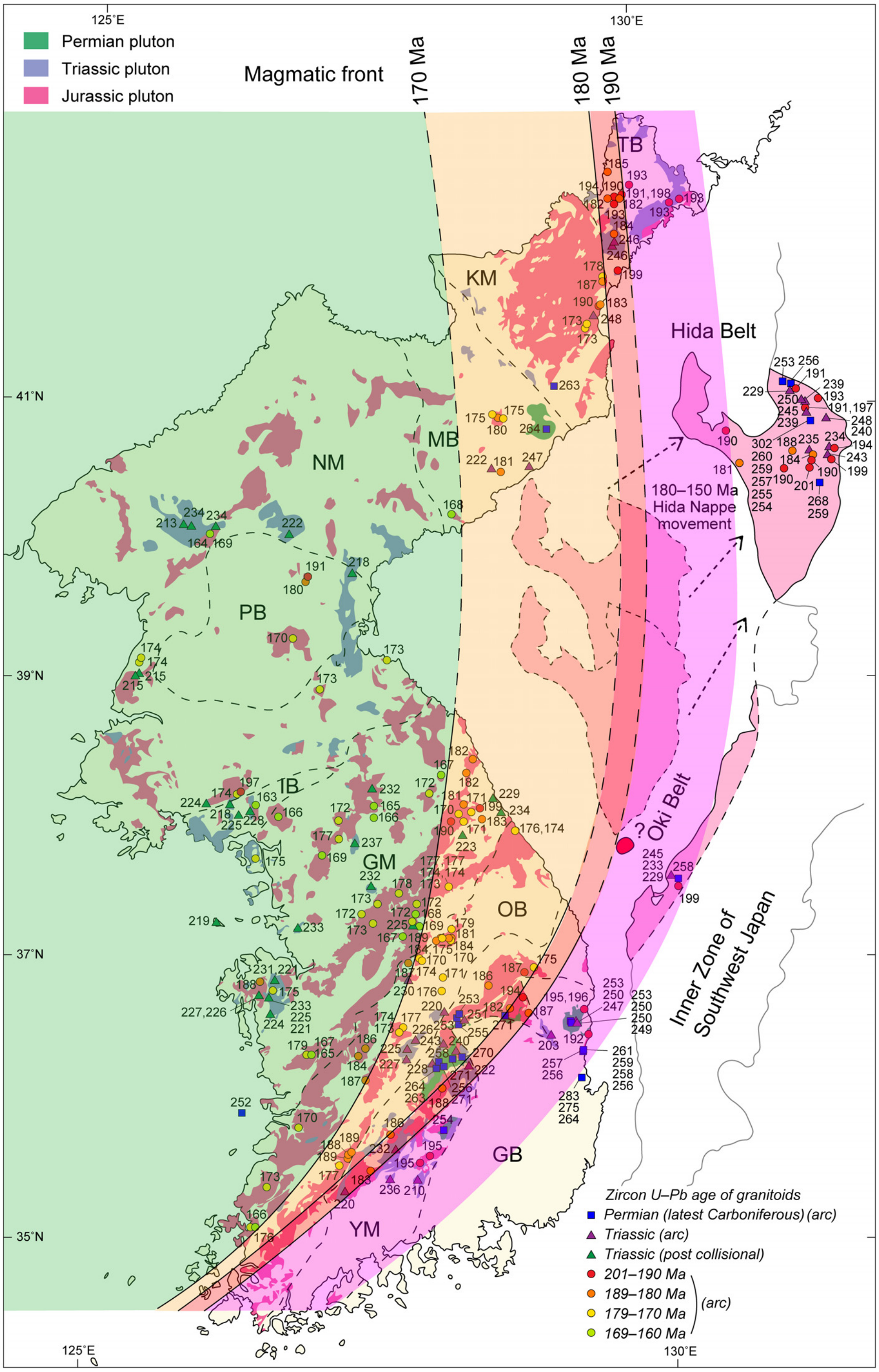

Fig. 6. Estimated position of the Jurassic magmatic front along the Korean Peninsula to the proto-Japanese Islands for a 10 Myr interval. The probable paleoposition of the Hida Belt is also illustrated in this figure.

connected or disconnected. The Hida Belt may have connected to one of the arc belts on the southeastern and northeastern margins of the Korean Peninsula based on the exposure of Permian to Triassic arc magmatic rocks in the Hida Belt. These arc magmatic rocks along the Korean Peninsula may have supplied Permian to Triassic detrital zircons to Permian-Triassic accretionary complexes and high-pressure metamorphic complexes in the Inner Zone of Southwest Japan. However, the Permian arc magmatic rocks in the Korean Peninsula and Hida Belt are minor in the currently exposed area (Figs. 1, 2). This small volume of Permian magmatic rocks is unlikely to have supplied a large number of detrital zircons to the trench. This implies that the Permian arc magmatic rocks were more widely distributed along the Korean Peninsula than the present exposure. In addition, the Permian arc was rapidly eroded and supplied a large amount of detritus to the trench. This scenario can explain the large population of Permian detrital zircons in the Permian-Triassic (meta-)sedimentary rocks within the Akiyoshi or Suo Belts, Inner Zone of Southwest Japan (Tsutsumi *et al*., 2000; Zhang *et al*., 2018a, 2018b; Kawaguchi *et al*., 2021). Based on their present localities, most of the Permian to Triassic arc igneous rocks formed along the continental margin (Figs. 1, 4). In previous studies, significant effects of tectonic erosion along convergent margins have been proposed (e.g., von Huene and Lallemand, 1990). Tectonic erosion may have played an important role in the extinction of the Permian arc due to its position as a continental margin. In contrast to the Permian to Triassic plutons, Jurassic plutons are more abundant on the continental side (Fig. 4), indicating their stable character from tectonic erosion.

Permian granitoids in the Southern Maizuru Belt (Fig. 2; Table 1) have a plagiogranite composition (Herzig *et al*., 1997). Moreover, the Permian granitoids in the Southern Maizuru Belt that accompany the voluminous mafic igneous rocks of the Yakuno ophiolite formed in an intraoceanic arc setting (Ishiwatari, 1985, 1999; Suda and Hayasaka, 2009; Suda *et al*., 2014). Therefore, the Permian granitoids in the Southern Maizuru Belt are tectonically different from the Permian continental arc that is expected along the Korean Peninsula. As discussed, revealing the paleogeography of the Permian arc-trench system is extremely important to constrain the continental marginal tectonics as well as collisional tectonics between the North China and South China Cratons at the eastern margin of East Asia. Therefore, more studies will be needed to confirm the results and suggestions of this study.

5. Summary remarks

1) Permian to Triassic granitoids occur throughout the whole Korean Peninsula with a special distribution pattern. The late Early Permian to Late Triassic granitoids formed in an arc tectonic setting (ca. 280-215 Ma) and are abundant in the Gyeongsang Basin and Yeongnam Massif of the southeastern Korean Peninsula and the Tumangang Belt, Kwanmo Massif, and Machollyong Belt of the northeastern Korean Peninsula. In contrast, the Late Triassic granitoids (ca. 235-225 Ma) formed in a post-collisional tectonic setting are commonly found in the Gyeonggi Massif, Imjingang Belt, and Nangrim Massif.

2) Permian to Jurassic granitoids are scarce in the Japanese Islands, and most of them occur in the Hida Belt. The Permian to Jurassic granitoids in the Hida Belt formed in an arc tectonic setting and display two major age clusters of ca. 260-230 Ma and ca. 200-180 Ma. This pattern of ages suggests that the Hida Belt was part of a volcanic arc that formed on the eastern margin of the Korean Peninsula and was probably located between the Permian-Triassic volcanic arcs in the southeastern and northeastern Korean Peninsula. The 200-180 Ma granitoids indicate that arc magmatism con-

tinued until 180 Ma but stopped at that time in the Japanese Islands.

3) The arc-related Jurassic granitoids (200-160 Ma) in the Korean Peninsula have a selective distribution pattern showing northwestward and westward-younging trends in the southern and northeastern Korean Peninsula, respectively, with a wide distribution of 180-160 Ma granitoids. This pattern indicates that the position of the magmatic front migrated toward the interior of the continent from 200 to 170 Ma due to the shallowing angle of subduction, and flat subduction occurred during 180-160 Ma. This evolution of the subduction style was most likely induced by the subduction of oceanic plateaus, which caused buoyancy.

4) The Hida Belt may have developed in a missing part of the continental arc between the continental arcs that existed in the southeastern and northeastern parts of the Korean Peninsula.

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