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Provenance Study of Pre-Neogene Sandstones in the Japanese Islands

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Abstract. Sandstone is one of the most common rock-types in the Japanese Islands. It occurs as a constituent of the accretionary complex and non-marine or shallow marine sequence. We analyzed detrital monazites in the pre-Neogene sandstones to obtain their provenance. An electron probe micro analyzer (EPMA) has been used to measure the U–Th–Pb ages of more than 15,000 detrital monazites in the islands. The age data were compared with those from the recent river sands in East Asia that represent their probable provenance area. Although ages of the sandstones are various, major provenances are divided into three types; (1) bimodal type with peaks at 100–300 Ma and 1850–1900 Ma; (2) major peak around 500 Ma or (3) at 400–450 Ma. Sandstones with a bimodal pattern (1) were derived mainly from the Korean Peninsula and coastal zone of China. Sandstones with ages of (2) 500 Ma and (3) 400–450 Ma peaks were derived from the Russian side of Far East Asia and the South China Craton, respectively.

Most of the sandstones in the Jurassic to Cretaceous accretionary complexes have a bimodal pattern. Paleogene sandstones in the Shimanto Belt from Kyushu to Okinawa have a peak at 400–450 Ma, whereas those from Kanto to Shikoku have a peak at 500 Ma. The former monazites were derived from the area including the South China Craton and the latter from the Russian side. Most non- and shallow-marine sandstones have a bimodal pattern. Sandstones with a peak at 500 Ma occur sporadically in the islands: northern Hokkaido (Yezo and Saroma groups, Cretaceous), the Hida area (Tetori Group: Cretaceous), and Maizuru (Nabae-Yakuno Group: Triassic). These classifications and provenances for the sandstones are important when we determine a tectonic reconstruction of the Japanese Islands.

Key words: monazite, age, sandstone, Japanese Islands

Introduction

The Japanese Islands are composed of complex geological units. Except for the granitic and volcanic rocks, basements consist mainly of an accretionary complex and its metamorphic equivalent with a subordinate amount of non- and shallow-marine sequence (Fig. 1). Strike-slip movement and the rotation of blocks are common in the islands. Many tectonic reconstruction models have been presented for the islands. The most outstanding movements are the opening of the Sea of Japan at around 20 Ma (Otofuji & Matsuda, 1983) and the strike-slip movement of the huge faults such as the Median Tectonic Line, the Tanakura Tectonic Line and many other faults.

The present study examines pre-Neogene sandstones in the islands to obtain the provenances of detrital minerals on the basis of the age distribution of monazite. The result will contribute to the tectonic reconstruction of the islands. The age determination of individual mineral grains has provided a powerful tool for provenance studies. Many age dating methods have been applied to the provenance studies of zircon, for example the Sensitive High-Resolution Ion Microprobe (SHRIMP) (e.g. Ireland, 1991; Tsutsumi *et al*., 2003), fission-track dating (e.g. Garver *et al*., 1999), inductively coupled plasma

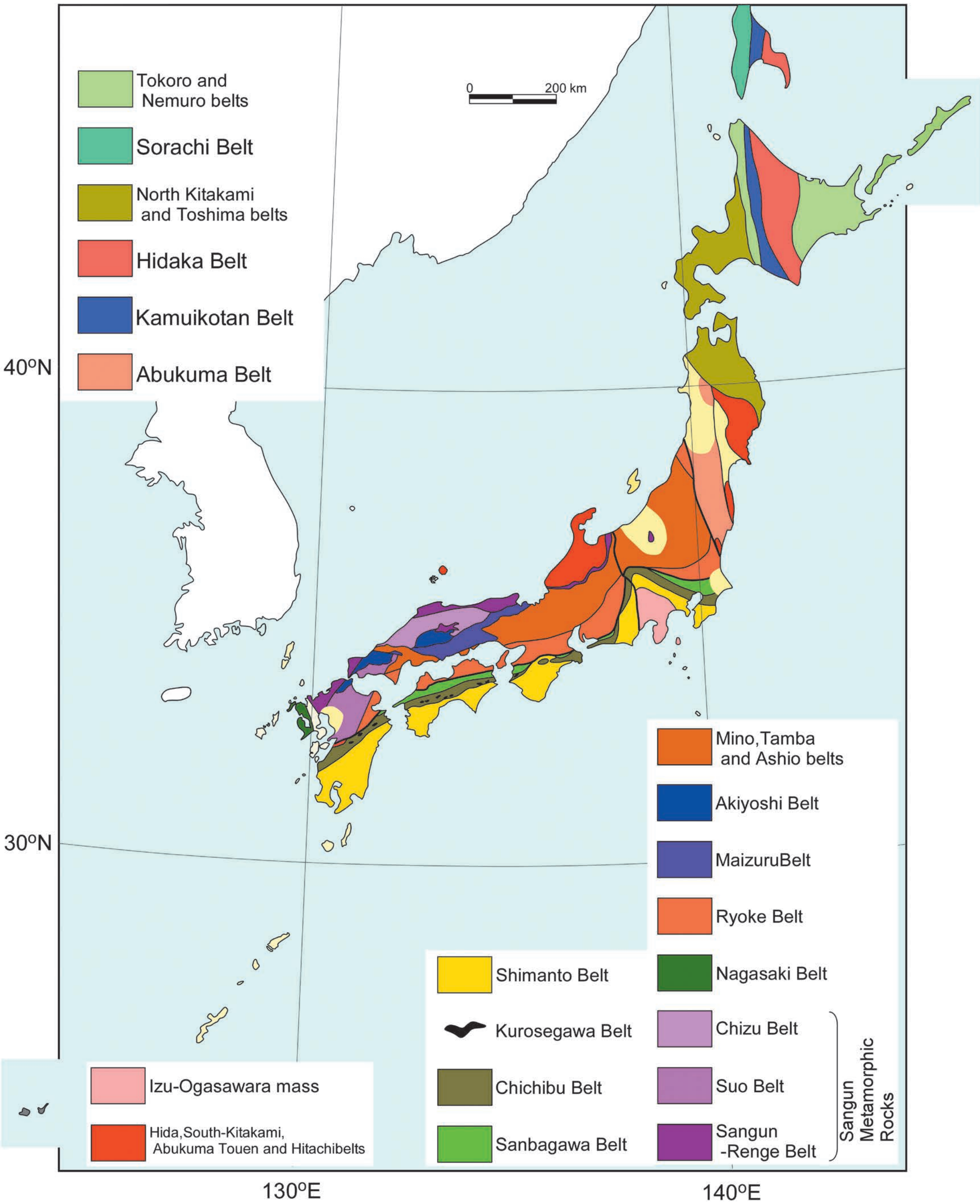

Fig. 1. Geological division of the basement rocks in the Japanese Islands.

mass spectrometry (ICP-MS) (e.g. Evans *et al*., 2001; Wyck & Norman, 2004), and by monazite age via the electron probe micro-analyzer (EPMA) (e.g. Suzuki *et al*., 1991; Fan *et al*., 2004; Yokoyama *et al*., 2007).

Monazite is present in granitic rocks and high-grade metamorphic rocks such as gneiss and amphibolite. It also occurs as a detrital mineral in

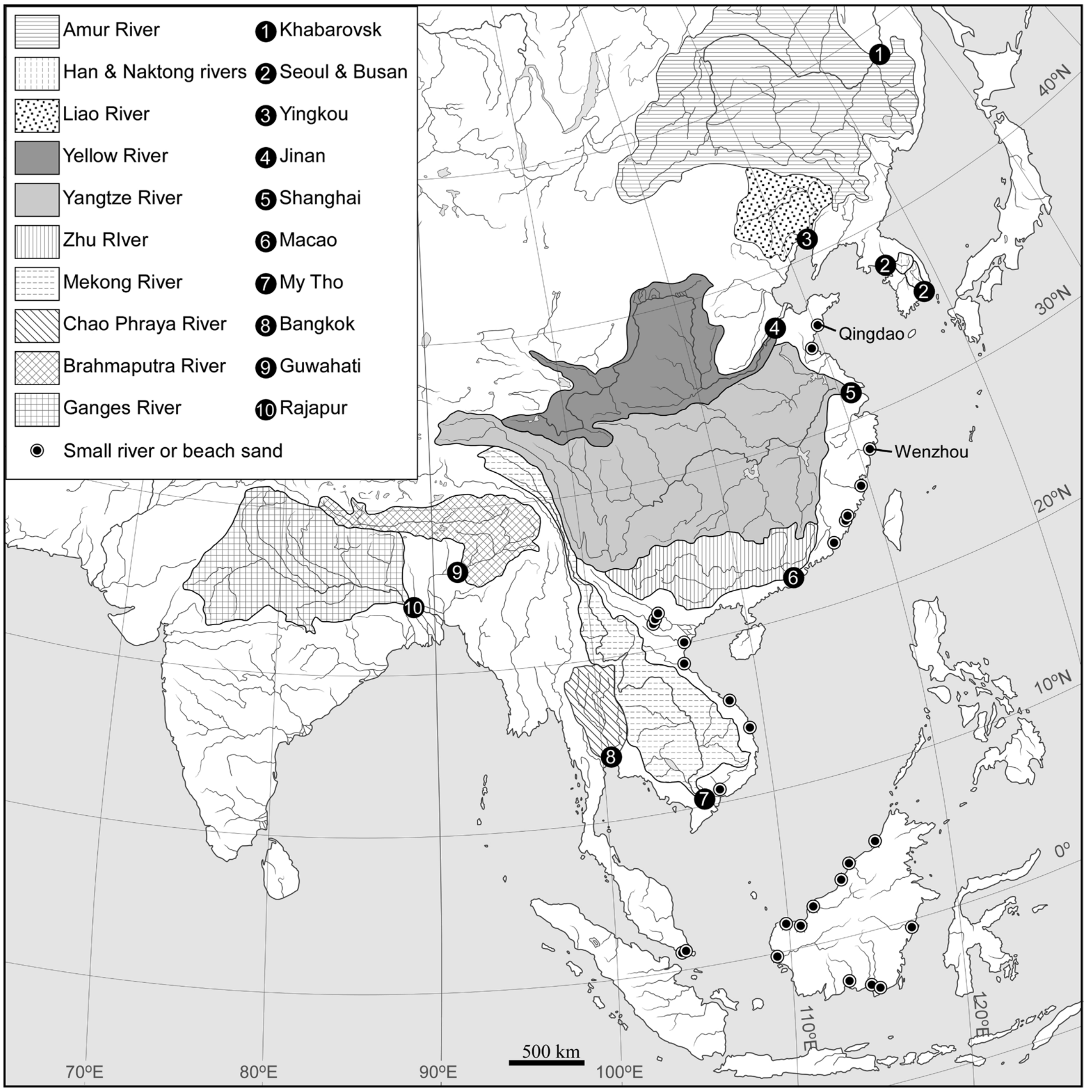

Fig. 2. Sampling localities of sands from the rivers in Asia. The age data of the sands were already published by Yokoyama *et al*., 2007, 2008, 2010a, 2010b, 2012 & 2015).

sandstone. Monazite is treated as an ultrastable mineral similar to zircon. However, it easily decomposes into rare earth element (REE)-bearing minerals under metamorphic conditions, even in weakly metamorphosed rocks. Even though there is a weakness for its decomposition, which is different from an ultrastable zircon, the age distribution of monazite is simpler than that of zircon due to restricted sources of monazite. As age data of monazites in the sands from the rivers cutting through the coastal provinces of Asia have already been reported (Fig. 2: Yokoyama *et al.*, 2007, 2010 & 2012), the monazite age data in the sandstones from the Japanese Islands will be a strong tool for provenance study.

Each river sample in East Asia has its distinct age distribution characteristics reflecting the different rocks in their drainage basins. In the Korean Peninsula, monazite age shows a clear bimodal pattern with clusters at 100–300 Ma and 1800–1900 Ma and monazites with ages from 300 Ma to 1800 Ma are scarce. A similar bimodal pattern is observed for the sands collected from coastal areas of China: Qingdao and Wenzhou (Fig. 2: Yokoyama *et al*., 2007 & 2012). Sands from the Yellow and Yangtze rivers have age peaks at 100–300 Ma, 410 Ma and ca.1900 Ma. The strongest peak appears at 0~25 Ma for the Yangtze River. The youngest monazites were almost certainly derived from the Himalayan region that has been a part of the river's drainage basin since the earliest Pleistocene (Fan *et al*., 2004). Such young data should therefore be excluded from consideration in provenance studies in the pre-Neogene sandstones in the Japanese Islands. A cluster of ages between 700 and 1000 Ma in the age distribution pattern of the Yangtze River is relatively high and is representative of the South China Craton (Wang, 1986). The Pliocene and Early Pleistocene sandstones in the drill core from the mouth of the Yangtze River have similar peaks to those of the modern sands except for a shift of the 450 Ma peak in the Pliocene sands to 410 Ma in Recent sand (Fan *et al*., 2004). Sand from the Amur River cutting through Siberia and northern China has a strong peak at 500 Ma, which is different from the other rivers in East Asia.

Sandstone samples

A detailed geological map of the Japanese Islands is presented by the Geological Survey of Japan. Many authors used a simplified map for basement rocks of the islands except for the granitic and volcanic rocks as shown in Fig. 1. Sandstones are present as one of the major constituents in the accretionary complex and terrestrial sequences including shallow marine in origin. Monazite is usually a rare mineral. It is easily decomposed into REE minerals even under low-grade metamorphism, but is well preserved in non-metamorphosed sandstones. Tsutsumi *et al*. (2003) completed the provenance study using an ultrastable mineral, zircon, even in the metamorphic rocks. In this study, we only analyzed detrital monazite in the non-metamorphosed sandstones.

Accretionary complexes in the islands occur as a belt and range in age from the Early Paleozoic to the Paleogene. The sandstones studied in this paper are from the Mino-Ashio Belt (Jurassic), the Chichibu belt (Jurassic to Lower Cretaceous) the North Kitakami Belt (Jurassic to Lower Cretaceous), the Iddonnappu Belt (Cretaceous) and the Shimanto Belt (Cretaceous to Paleogene) (Fig. 3). The Shimanto Belt includes partly Early Miocene sediments and also includes locally shallow-marine sediments. Although the essential members are from the deep-sea in origin, the constituents of the Shimanto Belt are tentatively treated here as a Cretaceous to Paleogene accretionary complex. Permian sandstones from the Maizuru Belt were studied and published by Yokoyama *et al*. (2009). Many sandstone samples were collected from each belt and are stored in the National Museum of Nature and Science, Tokyo.

Non- or shallow-marine sandstones occur sporadically in the islands. Among them, samples were collected mostly from South Kitakami (Jurassic to Lower Cretaceous), the Chichibu Belt (Jurassic and Cretaceous) and the Tetori Group (Cretaceous). A few samples were collected from the Yezo Group (Cretaceous), northern Hokkaido, and its northern extension (Sakhalin) (Fig. 4). The sandstones were also collected from the Choshi Group in the Kanto Province (Cretaceous), the Higuchi Group in central Chugoku Province (Early Jurassic), and the Himenoura Group in western Kyushu Province (Cretaceous). There are many other non- and shallow- marine sandstones in the islands. Among them, the Triassic to Cretaceous sandstones (Mine Group, Toyora Group and others) in western Chugoku Province, Triassic sandstones at Wakasa Bay (Nabae-Yakuno Group) and the Latest Cretaceous sandstones (Izumi Group) along the Median Line were already reported by Yokoyama *et al*. (1998, 2000 & 2009).

Analytical Procedures

Procedures for the separation of heavy minerals including monazite are the same as have been

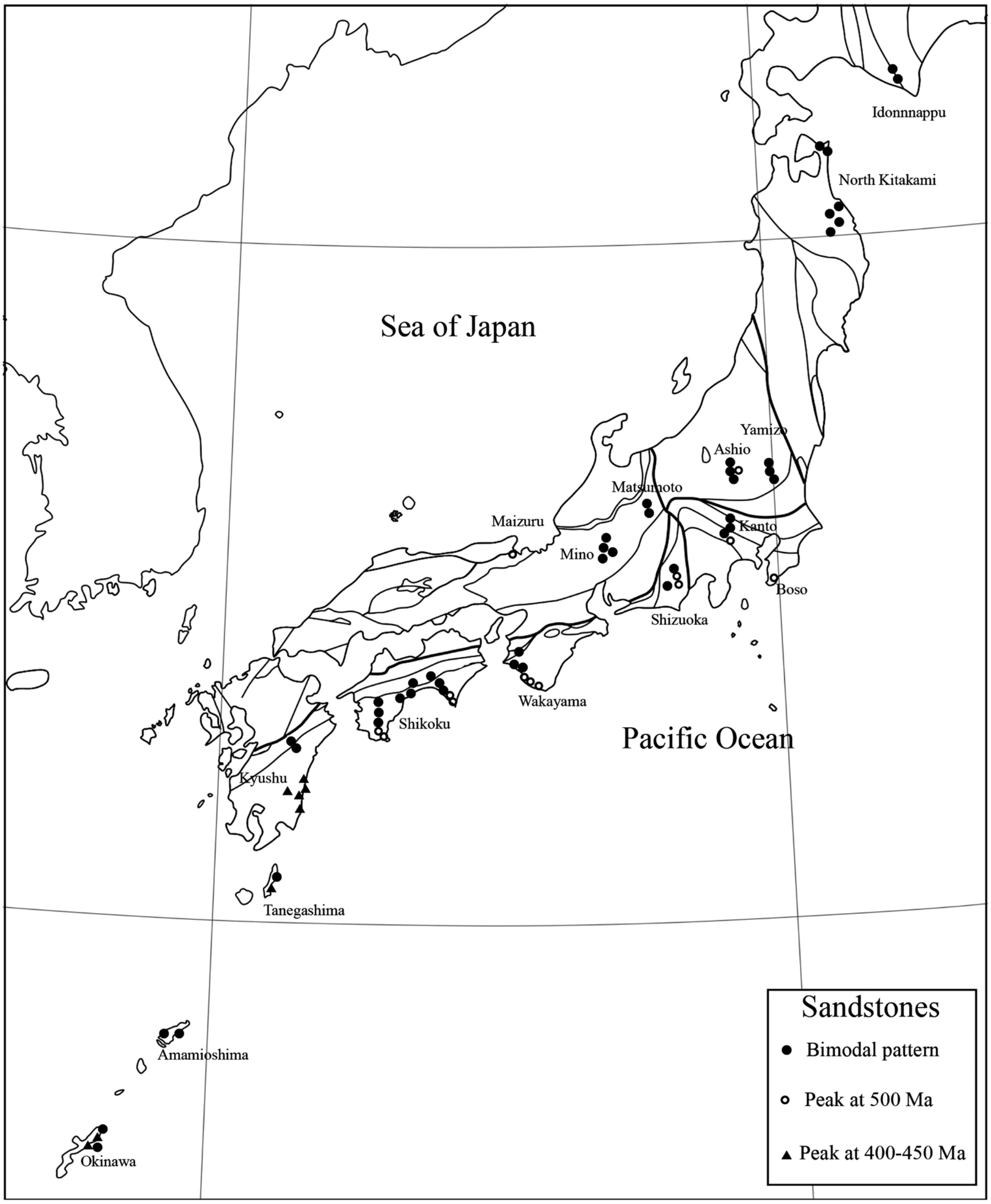

Fig. 3. Sampling sites of sandstones in the accretionary complexes including previously studied sites.

described by Yokoyama *et al*. (1990). The theoretical basis for monazite age calculation is essentially the same as that developed by Suzuki *et al*. (1991). Monazites were analyzed by electron probe micro-analyzer, EPMA, fitted with a Wavelength Dispersive Spectrometer (WDS). The EPMA, JXA-8800, is situated in the National Museum of Nature and Science. Analytical conditions have been described by Santosh *et al*. (2006). 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). Apart from minor shifts due to machine drift and variations

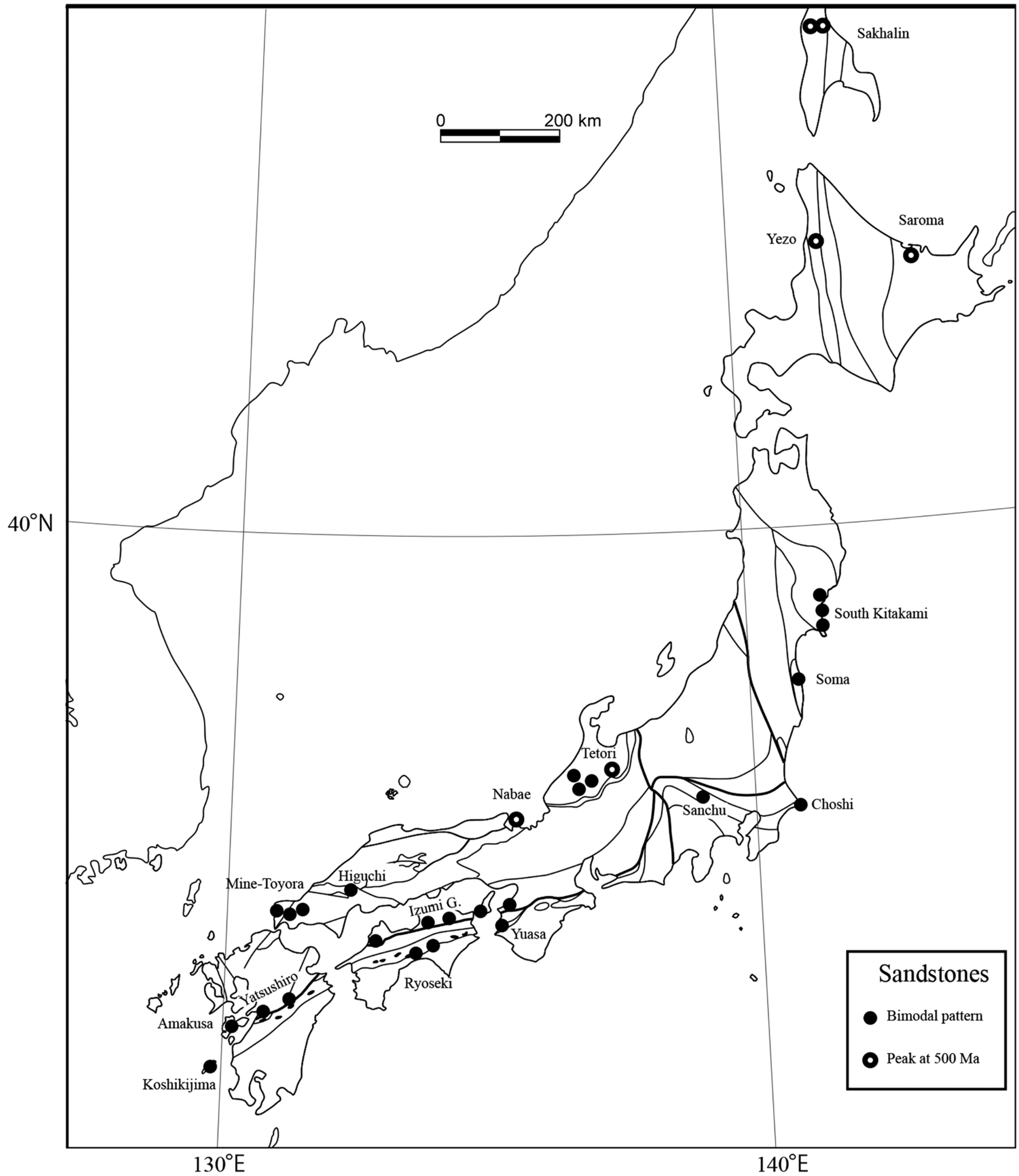

Fig. 4. Sampling sites of sandstones in the non- and shallow-marine sequences including previously studied sites.

in standard conditions, the ages obtained from the techniques were found to have good consistency. Monazites with ages of 3020 Ma and 64 Ma that were obtained by SHRIMP and K–Ar methods, respectively, have been used as internal standards for age calibration. The standard deviation of the age depends mostly on PbO content of the monazite. The error for the age is within a few percent for most of the analyzed monazites that were rich in ThO_2. If the age error exceeded 25 Ma for Mesozoic to Cenozoic monazites and/or 50 Ma for older monazites, these data were excluded from the figures and further discussion.

All the analytical positions were selected from back-scattered electron images and metamictised areas/zones were avoided. The standard deviation of ages within a single grain is mostly less than a few percent in old monazites (>ca. 100 Ma) or less than 25 Ma in younger monazites (<ca. 100 Ma). If a doubtful age was obtained, age analyses were repeated and one representative age has been selected for each grain.

Age of Monazite

Sandstones in the accretionary complexes: Among the various types of accretionary complexes in the Japanese Islands, one of the old accretionary complexes is the Maizuru belt from the Permian. The ages of monazites from the Maizuru Belt have a strong peak at 500 Ma. Yokoyama *et al.* (2009) concluded that they were derived from the Khanka and Jiamusi blocks in Russia before the amalgamation of northern China Craton and the Khanka-Jiamusi Block during the Triassic. Permian or older accretionary complexes are the Akiyoshi Belt, the Nedamo Belt and the Sangun belt in the Japanese Islands, but detrital monazite has not been preserved.

More than 7000 monazite grains in the sandstones from the accretionary complex have been analyzed. All the age data are summarized in Table 1. Although many samples were collected from each belt, detrital monazite is not always preserved. The age data obtained from each belt are summarized in the same diagram as either sufficient age data was not obtained or the samples show a similar age distribution. Age distributions of monazites are presented as probability diagrams in Figs. 5 and 6. Probability distributions for monazite ages were calculated with a multi-peak Gauss fitting method (Williams, 1998). Age patterns of the sands from the rivers in East Asia were reproduced for comparison in Fig. 7.

Detrital monazite is more or less preserved in the sandstones from the Jurassic to Lower Cretaceous accretionary complexes. The studied samples are from the Mino and Matsumoto areas in the Mino Belt, the Ashio–Yamizo Belt, the North Kitakami Belt and the Chichibu Belt. The age distribution patterns are shown in Fig. 5. Most of them show a bimodal pattern with peaks at 200–300 Ma and 1850–1900 Ma which is similar to those from the Korean Peninsula and/or present southern coast zone of the China Craton (Yokoyama *et al*., 2012).

Sandstones in the Chichibu Belt including part of a Lower Cretaceous formation are metamorphosed weakly, and then monazite was not well preserved. Only restricted sandstones contain detrital monazite with a bimodal age distribution as well as the other Jurassic accretionary complex. A few samples from the Ashio Belt have a peak at 500 Ma in addition to 1850–1900 Ma and 200–300Ma peaks (Fig. 5). The monazite with 500 Ma is present in the Khanka or Jiamusi blocks and is common in the sand from the Amur River (Yokoyama *et al*. 2009). As discussed by Yokoyama *et al*. (2001), it is reasonable to conclude that the provenance of a few sandstones in the Ashio Belt was both the Korean Peninsula and also the Khanka-Jiamusi Block.

The Shimanto Belt occurs from the Kanto Province to Okinawa through Shikoku and Kyushu (Fig. 1). The Cretaceous sandstones from Kanto to Okinawa have a bimodal pattern similar to those in the Jurassic and Lower Cretaceous accretionary complexes (Fig. 6). On the other hand, Paleogene sandstones have three patterns in their monazite age distribution. The sandstones from Kanto to Shikoku have peaks at 500 Ma and 2500 Ma in addition to 200–300 Ma and 1850–1900 Ma (Fig. 6). The pattern is similar to that of the present Amur River (Fig. 7). On the other hand, two patterns are recognized for the sandstones from Kyushu to Okinawa. One is a bimodal pattern, possibly derived from the Korean Peninsula. The other has a complex age pattern with peaks at 200–300 Ma, 400–450 Ma, 1800–1900 Ma and 2500 Ma. A weak cluster at 700–1100 Ma is also recognized. This kind of age pattern is similar to that of the Yangtze River.

The Cretaceous accretionary complex, the Iddonnapu Belt in Hokkaido, occurs at the western margin of the Hidaka low-pressure type metamorphic belt. The sandstones in the belt have

Table 1. Age data from the sandstones in the accretionarys complexes in the Japanese Islands.
*Abbrebiation: Iddo= Iddonnapu, Kant–Shiz=Kanto–Shizuoka, Waka–Shik=Shinmanto from Wakayama to Shikoku, Kyu–Oki=Shimanto from Kyushu to Okinawa, Akka=Akka, Ash–Yam=Ashio–Yamizo, Min–Mat=Mino–Matsumoto, Chic=Chichibu, Cret=Cretaceous, Paleg=Paleogene, Jur=Jurassic, Lcret=Lower Cretaceous.

Area*	Iddon	Shi-manto	Kant–Shiz	Waka–Shik	Kyu–Oki	Kyu–Oki
Age*	Cret	Cret	Paleg	Paleg	Palg-1	Palg-2
0	0	0	0	0	0	0
0.25	0	0	0	1	4	1
0.5	0	20	7	17	4	1
0.75	0	35	13	62	4	1
1	0	24	23	44	15	2
1.25	3	15	19	33	42	5
1.5	22	41	27	33	60	22
1.75	16	50	32	46	50	27
2	16	46	34	49	117	23
2.25	16	56	39	44	118	73
2.5	1	34	27	31	52	47
2.75	0	7	8	16	15	5
3	0	0	6	2	1	2
3.25	0	0	1	0	3	0
3.5	0	0	0	1	7	0
3.75	0	0	0	2	11	0
4	0	0	4	5	25	0
4.25	0	0	4	4	30	2
4.5	0	1	12	11	25	0
4.75	0	0	25	32	19	1
5	0	0	22	31	14	0
5.25	0	0	11	16	3	0
5.5	0	0	1	2	2	0
5.75	0	0	1	0	0	0
6	0	0	0	0	0	0
6.25	0	0	0	0	0	0
6.5	0	0	0	0	0	0
6.75	0	0	0	0	1	0
7	0	0	1	0	2	0
7.25	0	0	0	1	2	1
7.5	0	0	0	0	1	0
7.75	0	0	0	0	5	0
8	0	0	0	0	10	1
8.25	0	0	0	0	7	2
8.5	0	0	0	0	6	2
8.75	0	0	0	0	3	0
9	0	0	0	0	0	0
9.25	0	0	0	0	0	0
9.5	0	0	0	0	2	0
9.75	0	0	0	1	0	0
10	0	0	0	0	0	0
10.25	0	0	0	1	0	0
10.5	0	0	0	0	1	0
10.75	0	0	0	0	1	0
11	0	0	0	0	2	0
11.25	0	0	0	0	0	0
11.5	0	0	0	0	0	0
11.75	0	0	0	0	0	0
12	0	0	0	0	0	0
12.25	0	0	0	0	0	0
12.5	0	0	0	0	0	0
12.75	0	0	0	0	0	0
13	0	0	0	0	1	0
13.25	0	0	1	0	0	0
13.5	0	0	0	0	1	0
13.75	0	0	0	0	0	0
14	0	0	0	0	0	0
14.25	0	0	0	0	0	0
14.5	0	0	0	0	0	0
14.75	0	0	0	0	0	0
15	0	0	0	0	0	0
15.25	0	0	0	0	0	0
15.5	0	0	1	0	0	0
15.75	0	0	0	0	1	0
16	0	0	0	0	0	0
16.25	0	0	0	1	1	0
16.5	0	0	0	0	0	0
16.75	0	0	0	0	0	0
17	0	0	0	1	1	0
17.25	0	0	1	5	0	0
17.5	0	7	5	5	8	1
17.75	1	11	9	23	28	0
18	0	21	32	52	62	8
18.25	5	22	57	64	82	19
18.5	4	31	57	94	128	33
18.75	4	34	69	75	149	56
19	3	17	58	51	154	45
19.25	1	13	55	20	114	60
19.5	0	6	27	21	52	37
19.75	0	4	20	19	43	19
20	0	2	16	5	10	9
20.25	0	0	6	5	2	5
20.5	0	1	6	0	3	0
20.75	0	3	7	1	2	0
21	0	0	3	0	1	0
21.25	0	0	3	0	0	0
21.5	0	1	3	0	0	0
21.75	0	0	0	0	0	0
22	0	0	0	0	1	0
22.25	0	1	1	0	0	0
22.5	0	0	0	0	1	0
22.75	0	0	0	0	0	0
23	0	0	0	0	0	0
23.25	0	0	1	1	1	0
23.5	0	0	1	0	0	0
23.75	0	0	1	1	0	0
24	0	0	1	1	3	0
24.25	0	0	1	1	1	0
24.5	0	0	0	0	0	1
24.75	0	0	1	3	3	0
25	0	0	2	1	2	0
25.25	0	0	1	3	3	0
25.5	0	0	1	0	5	1
25.75	0	0	0	0	2	1
26	0	0	1	1	1	0
26.25	0	0	1	0	1	0
26.5	0	0	0	0	0	0
26.75	0	0	0	0	0	0
27	0	0	1	0	0	0
27.25	0	0	0	0	0	0
27.5	0	0	0	0	0	0
27.75	0	0	0	0	0	0
28	0	0	0	0	0	0

Table 1. (continued)

Area	Akka	Ash–Yam	Ash–Yam	Min–Mat	Chi
Age	Jur-Lcret	Jur-1	Jur-2	Jur	Jur-Lcret
0	0	0	0	0	0
0.25	1	0	0	0	0
0.5	0	0	0	0	0
0.75	0	0	0	0	0
1	0	0	0	0	0
1.25	2	0	0	0	0
1.5	17	7	3	40	19
1.75	31	18	1	58	37
2	33	55	2	139	61
2.25	66	146	5	306	50
2.5	33	83	7	94	74
2.75	10	24	1	15	59
3	0	3	0	1	11
3.25	0	2	0	2	2
3.5	0	0	0	0	2
3.75	0	1	0	1	0
4	0	0	1	2	0
4.25	0	3	1	1	0
4.5	0	2	0	3	0
4.75	0	1	7	0	0
5	0	2	6	3	1
5.25	0	1	0	0	2
5.5	0	0	0	0	1
5.75	0	0	0	0	0
6	0	0	0	0	0
6.25	0	0	0	0	1
6.5	0	0	0	0	0
6.75	0	1	0	0	0
7	0	0	0	0	0
7.25	0	0	0	0	0
7.5	0	0	0	0	0
7.75	0	0	0	2	0
8	0	1	0	0	0
8.25	0	1	0	0	0
8.5	0	0	0	1	0
8.75	0	0	0	0	0
9	0	0	0	0	0
9.25	0	0	0	2	0
9.5	0	0	0	0	0
9.75	0	0	0	0	0
10	0	0	0	0	0
10.25	0	0	0	0	0
10.5	0	0	0	0	0
10.75	0	0	0	0	0
11	0	0	0	0	0
11.25	0	0	0	0	0
11.5	0	0	0	1	0
11.75	0	0	0	0	0
12	0	0	0	0	0
12.25	0	0	0	0	0
12.5	0	0	0	0	0
12.75	0	0	0	0	0
13	0	1	0	0	0
13.25	0	1	0	0	0
13.5	0	0	1	0	0
13.75	0	0	0	0	0
14	0	0	0	0	0
14.25	0	1	0	0	0

Area	Akka	Ash–Yam	Ash–Yam	Min–Mat	Chi
Age	Jur-Lcret	Jur-1	Jur-2	Jur	Jur-Lcret
14.5	0	0	0	0	0
14.75	0	1	0	0	0
15	0	0	0	0	0
15.25	0	1	0	1	0
15.5	0	0	0	1	0
15.75	0	0	0	3	0
16	0	0	0	4	0
16.25	0	2	0	4	0
16.5	0	2	0	6	1
16.75	0	5	0	6	0
17	0	0	0	14	0
17.25	0	2	0	24	4
17.5	0	9	1	26	4
17.75	2	22	1	50	4
18	4	47	1	95	3
18.25	14	68	9	131	17
18.5	19	129	14	246	48
18.75	25	198	10	236	77
19	9	196	15	156	91
19.25	7	138	5	76	66
19.5	3	101	0	32	24
19.75	1	23	1	18	15
20	0	8	1	7	8
20.25	0	3	0	0	0
20.5	0	2	0	0	0
20.75	0	0	0	0	0
21	0	0	0	0	0
21.25	0	0	0	1	0
21.5	0	0	0	0	0
21.75	0	0	0	0	0
22	0	0	0	0	0
22.25	0	0	0	0	0
22.5	0	0	0	1	0
22.75	0	0	0	0	1
23	0	0	0	0	0
23.25	0	0	0	0	0
23.5	0	0	0	0	0
23.75	0	0	0	0	0
24	0	0	0	0	0
24.25	0	1	0	2	0
24.5	0	0	0	1	0
24.75	0	0	0	0	0
25	0	0	0	0	0
25.25	0	0	0	0	0
25.5	0	0	0	0	0
25.75	0	0	0	0	0
26	0	0	0	0	0
26.25	0	0	0	0	0
26.5	0	0	0	0	0
26.75	0	0	0	0	0
27	0	0	0	0	0
27.25	0	0	0	0	0
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27.75	0	0	0	0	0
28	0	0	0	0	0

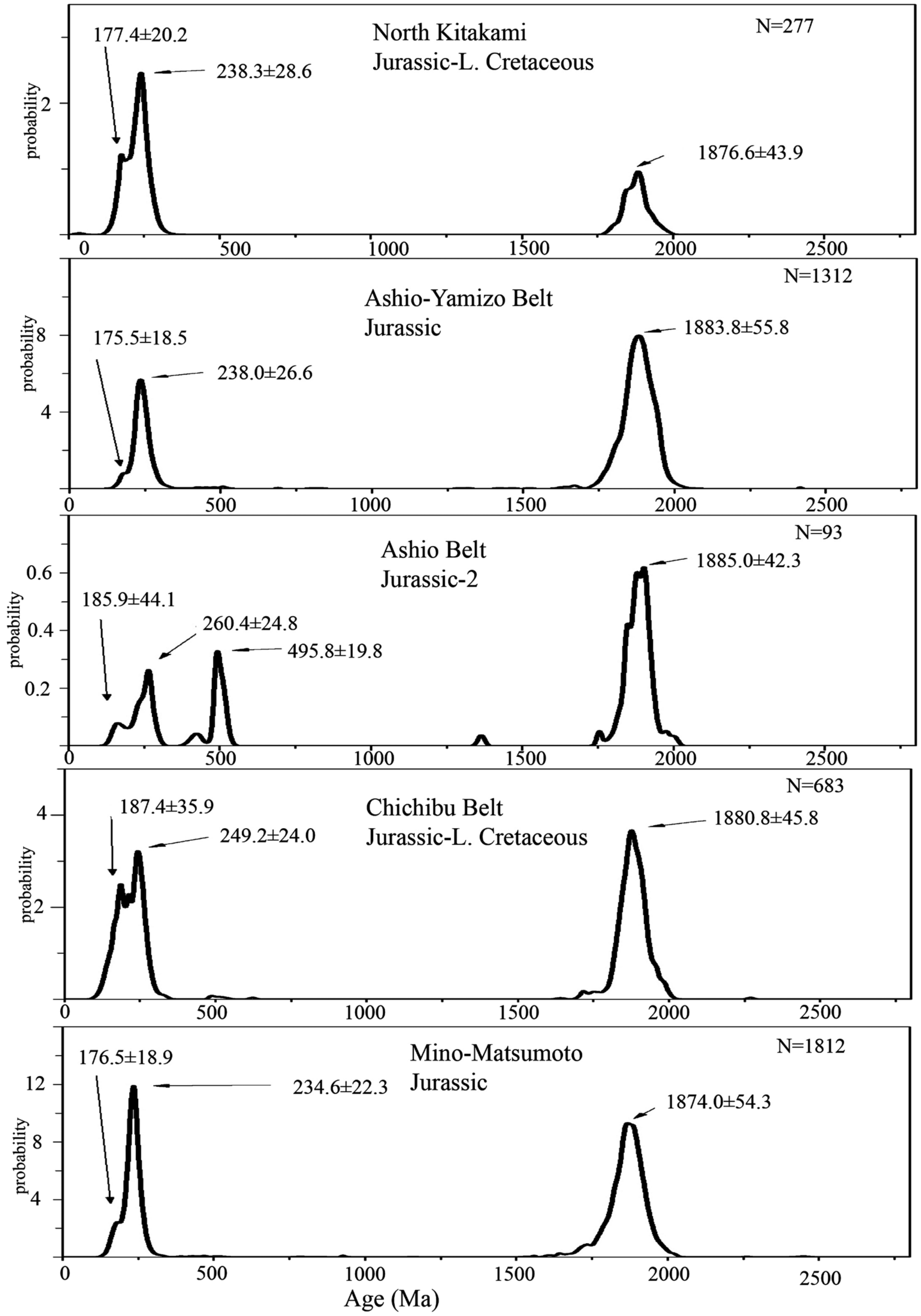

Fig. 5. Probability distribution of ages of detrital monazites in the sandstones from the accretionary complexes in the north and central part of the Japanese Islands. The numerical value (n) denotes the number of analyzed monazite grains.

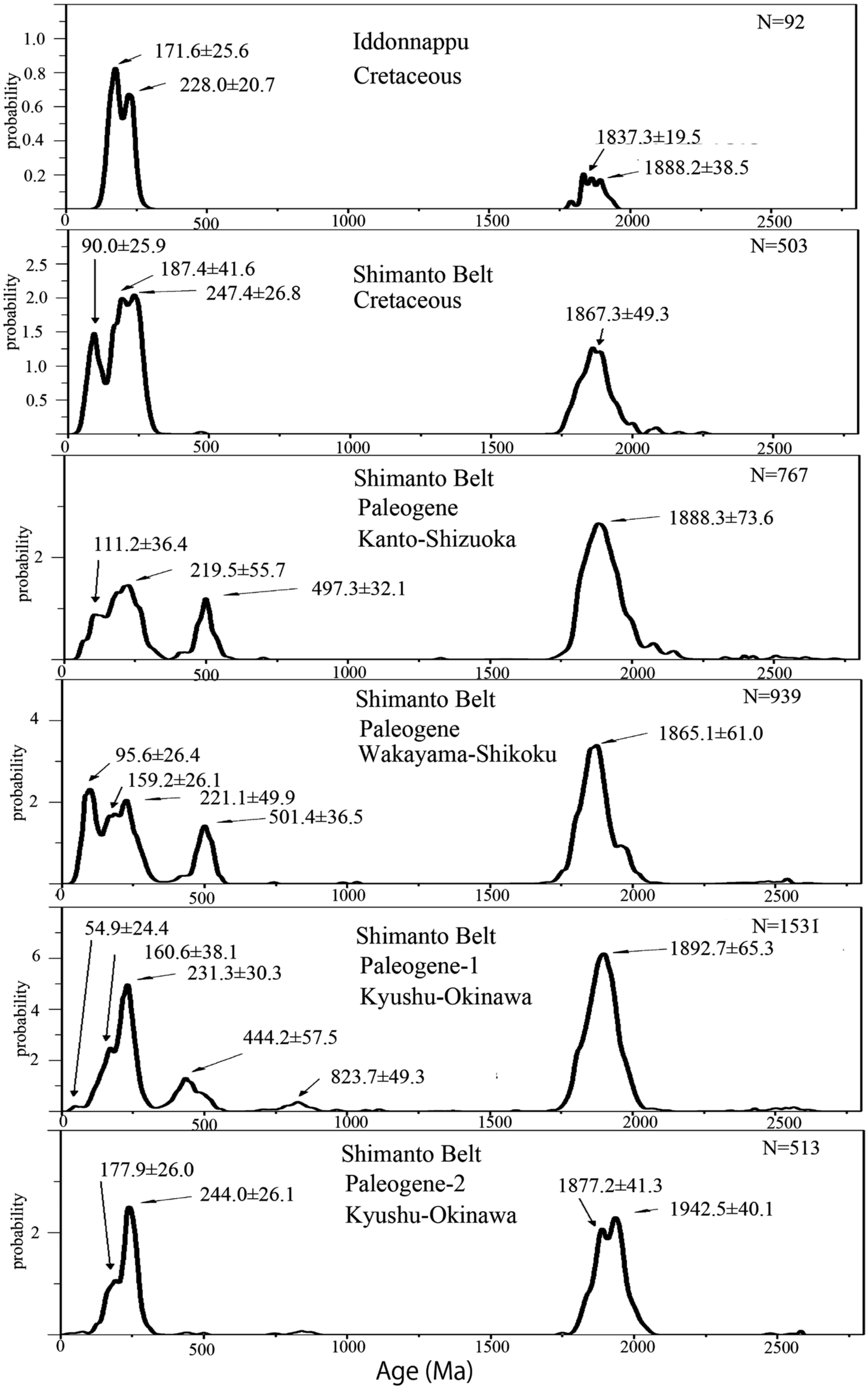

Fig. 6. Probability distribution for the ages of detrital monazites in the sandstones from the Iddonnappu Belt and Shimanto Belt. The numerical value (n) denotes the number of analyzed monazite grains.

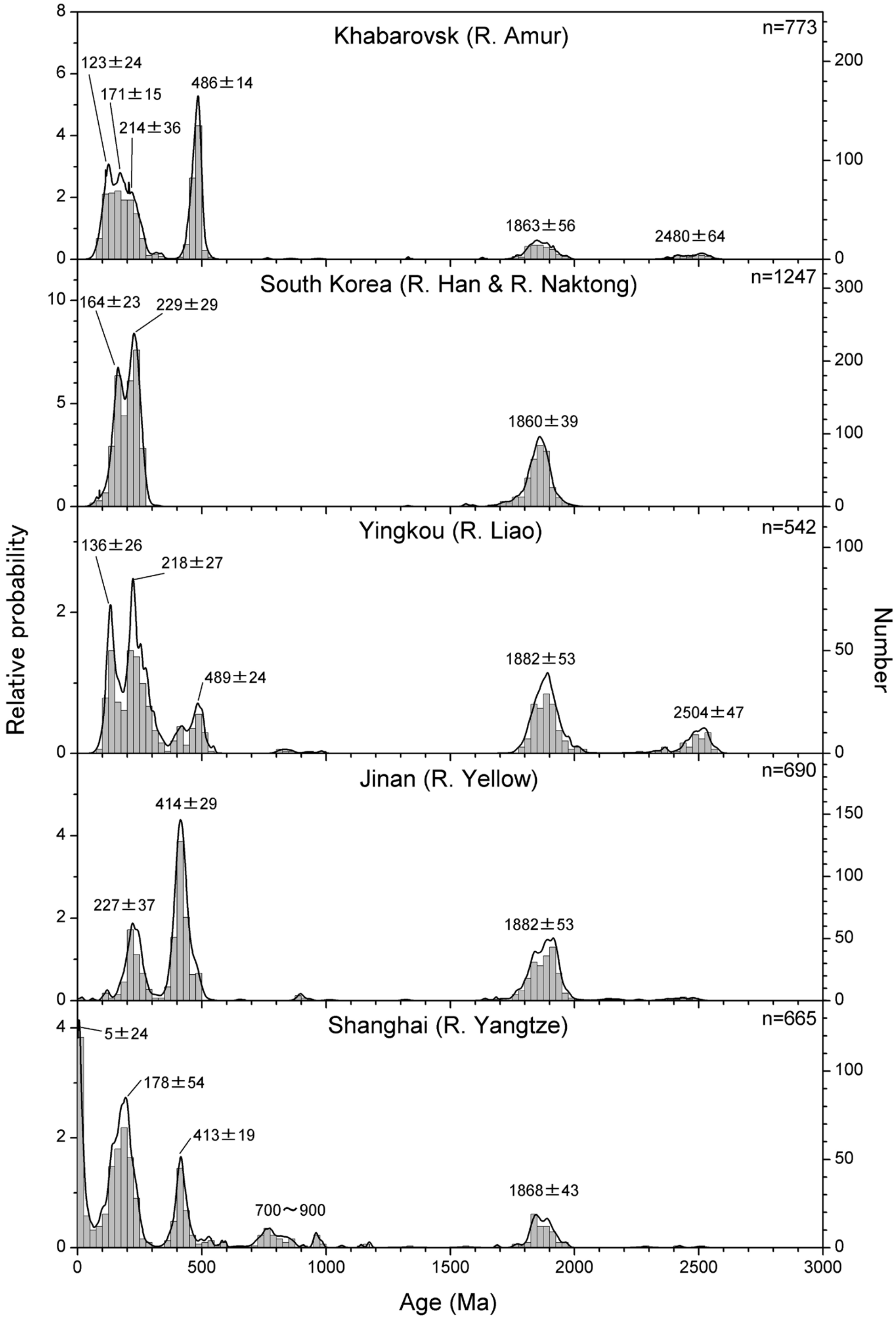

Fig. 7. Probability distribution of monazite ages in the sands from the major rivers in East Asia (After Yokoyama *et al*., 2007). The numerical value (n) denotes the number of analyzed monazite grains.

also a bimodal pattern similar to those in the Cretaceous Shimanto Belt. As far as the age is concerned, the Iddonnapu belt may be a part of the Shimanto Belt. However, the Upper Cretaceous accretionary complex has not been recognized between Kanto Province and Hokkaido.

Non- or shallow-marine sandstones: Most of the non- or shallow-marine sandstones in the Japanese Islands have been analyzed: the sandstones from the Yezo and Saroma groups in Hokkaido (Cretaceous), South Kitakami (Jurassic to Lower Cretaceous), Choshi Group in the Kanto Province (Cretaceous), Tetori Group (Cretaceous), Nabae-Yakuno Group (Triassic), Higuchi Group in the western Chugoku Province (Early Jurassic), Izumi Group along the Median Tectonic Line (Latest Cretaceous), Jurassic to Cretaceous formations along the Kurosegawa Tectonic Line in the Chichibu Belt and Himenoura Group in western Kyushu (Cretaceous). Most of the age patterns are bimodal similar to those in the Jurassic to Cretaceous accretionary complexes mentioned above. As reported by Yokoyama *et al.* (2009), the Nabae-Yakuno Group has a peak at 500 Ma, which was partly derived from the Khanka-Jiamusi Block. Age data from the South Kitakami and Tetori groups were reported by Yokoyama *et al.* (1996 & 2002). Additional samples were collected from the groups for this study. As a northern extension of the Yezo Group in Hokkaido, the Cretaceous to Paleogene sandstones in Sakhalin are also analyzed.

More than 7000 age data for monazite grains in the non- or shallow-marine sandstones have been obtained. All the age data are summarized in Table 2. Age distributions of monazites are presented as probability diagrams in Figs. 8 and 9.

Detrital monazites in the Saroma Group and Yezo Group in Hokkaido are rarely preserved. Whereas the Cretaceous sandstones in Sakhalin, the northern extension of the Yezo Group, contain abundant detrital monazites. These sandstones have a peak at 500 Ma as well as at 200–300 Ma and 1850–1900 Ma, similar to the present sands from the Amur River. Jurassic to Lower Cretaceous sandstones from the South Kitakami are represented by a typical bimodal pattern as shown in Fig. 8. The Tetori Group also has a typical bimodal pattern as studied by Yokoyama *et al.* (2002), but a few newly collected sandstones have a peak at 500 Ma (Fig. 8).

The Cretaceous sandstones in the Choshi Group have a very small peak at 500 Ma, but the monazite age pattern is almost bimodal. Cretaceous and Jurassic sandstones occur along the Kurosegawa Tectonic Line in the Chichibu Belt. They also have a bimodal pattern. Age pattern of the Early Jurassic sandstones in the Higuchi Group, central Chugoku Province, almost has one peak at 1850 Ma. Although a younger peak at around 250 Ma is almost negligible, the age pattern will be treated as a part of the bimodal pattern. Cretaceous sandstones from the Himenoura Group in both the Amakusa area and Koshikijima Islands also show a bimodal pattern.

Discussion

One of the most drastic movements in the Japanese Islands was the opening of the Sea of Japan during the Neogene. Although the strike-slip movement mostly developed around the continental margin, the East Asian continent has been more or less stable at least since the Triassic when the Chino-Korea, Khanka, and Jiamusi blocks were amalgamated. Constituents of the Japanese Islands were present at the continental margin of East Asia before the opening of the Sea of Japan. Hence, it is reasonable to consider that the provenance of the pre-Neogene sandstones in the islands were related with the present configuration. As shown in Fig. 7, the age data of the main rivers in Asia have been presented by Yokoyama *et al.* (2007). The data are available when we compare monazite age distribution data from the modern river systems with those in the sandstones from the Japanese Islands.

As shown in age distribution patterns from both of the accretionary complexes and non- and shallow-marine sequences, the bimodal pattern derived from the Korean Peninsula and its con-

Table 2. Age data of the non- or shallow-marine sandstones from the Sakhalin and Japanese Islands.
*Abbrebiation: Sakh=Sakhaline, Saro=Saroma, Kita=Kitakami-Soma, Chos=Choshi, Teto=Tetori, Chic=Chichibu, Higu=Higuchi, Amak=Amakusa, Kash=Kashikojima, Cret=Cretaceous, Pal=Paleogene, Ju&Jura=Jurassic

Area*	Sakh	Yezo	Saro	Kita	Chos	Teto	Teto	Chic	Chic	Higu	Amak	Kash
Age*	Cre-Pal	Cret	Cret	Ju-Cre	Cret	Cret1	Cret2	Cret	Jura	Jura	Cret	Cret
0	6	0	0	0	0	0	0	0	0	0	0	0
0.25	28	0	0	0	0	0	0	0	0	0	0	0
0.5	69	0	0	0	0	0	0	0	0	0	0	0
0.75	71	1	0	0	0	0	0	1	0	0	2	1
1	72	2	5	0	1	0	0	2	0	0	0	1
1.25	43	3	1	2	7	0	4	18	0	0	0	0
1.5	41	5	3	74	13	1	68	86	4	0	0	10
1.75	39	3	4	101	19	5	210	84	15	0	17	23
2	38	6	6	203	13	9	225	89	20	0	3	24
2.25	60	1	5	249	23	19	325	103	12	4	8	19
2.5	30	6	5	128	17	41	102	60	15	6	1	7
2.75	10	0	4	29	4	8	14	7	5	0	0	1
3	0	0	1	7	2	2	1	0	0	0	0	1
3.25	0	0	0	1	0	1	1	0	0	0	0	1
3.5	0	0	0	0	0	0	0	1	0	0	0	0
3.75	0	0	0	0	0	0	0	0	0	0	0	0
4	3	0	1	0	1	0	0	0	0	0	0	0
4.25	4	1	2	0	0	0	0	0	0	0	0	0
4.5	19	2	1	0	0	1	0	0	0	0	0	0
4.75	57	1	6	0	1	12	0	1	0	1	0	0
5	37	1	3	0	2	10	0	0	0	0	0	0
5.25	12	2	0	0	0	1	0	0	0	0	0	0
5.5	1	0	0	0	0	0	0	0	0	0	0	0
5.75	1	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
6.25	0	0	0	0	0	0	0	0	0	0	0	0
6.5	0	0	0	0	0	0	0	0	0	0	0	0
6.75	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
7.25	0	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0	0
7.75	0	0	0	0	0	0	0	0	0	0	0	0
8	0	1	0	0	0	0	0	0	0	0	0	0
8.25	0	0	0	0	0	0	0	0	0	0	0	0
8.5	0	0	0	0	0	0	0	0	0	0	0	0
8.75	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
9.25	0	1	0	0	0	0	0	0	0	0	0	0
9.5	0	0	0	0	0	0	1	0	0	0	0	0
9.75	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
10.25	0	0	0	0	0	0	0	0	0	0	0	0
10.5	0	0	0	0	0	0	0	0	0	0	0	0
10.75	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
11.25	0	0	0	0	0	0	0	0	0	0	0	0
11.5	0	0	0	0	0	0	0	0	0	0	0	0
11.75	0	0	0	1	0	0	1	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
12.25	0	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0	0
12.75	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
13.25	0	0	0	0	0	0	0	0	0	0	0	0
13.5	0	0	0	1	0	0	0	0	0	0	0	0
13.75	0	0	0	0	0	0	0	1	0	0	0	0

Table 2. (continued)

Area*	Sakh	Yezo	Saro	Kita	Chos	Teto	Teto	Chic	Chic	Higu	Amak	Kash
Age*	Cre-Pal	Cret	Cret	Ju-Cre	Cret	Cret1	Cret2	Cret	Jura	Jura	Cret	Cret
14	0	0	0	0	0	0	1	0	0	0	0	0
14.25	0	0	0	0	0	0	0	0	0	0	0	0
14.5	0	0	0	0	0	0	1	1	0	0	0	0
14.75	0	0	0	0	0	0	0	1	0	0	0	0
15	1	0	0	1	0	0	1	0	0	0	0	0
15.25	0	0	0	0	0	0	0	0	0	0	0	0
15.5	0	0	0	0	0	0	0	0	0	0	0	0
15.75	0	0	0	0	0	0	1	1	0	0	0	0
16	0	0	0	2	0	0	0	0	0	0	0	0
16.25	0	0	0	0	0	0	2	0	0	0	0	0
16.5	0	0	0	2	0	0	5	0	0	0	0	0
16.75	1	0	1	1	0	0	1	0	0	1	0	0
17	3	0	0	6	0	0	3	0	0	0	0	0
17.25	4	0	0	5	1	0	8	0	1	1	0	0
17.5	3	0	0	18	1	1	7	4	0	0	1	0
17.75	4	2	2	26	2	0	31	2	0	16	0	0
18	25	6	4	86	13	0	111	8	6	95	7	1
18.25	63	6	2	172	13	9	314	26	20	165	11	9
18.5	93	6	4	297	13	17	391	84	53	113	22	10
18.75	66	2	6	290	12	9	276	109	69	55	19	13
19	20	1	2	172	9	5	165	46	25	16	13	12
19.25	3	1	2	84	1	1	77	17	4	2	12	5
19.5	2	0	0	31	4	0	22	5	0	0	0	0
19.75	0	0	0	9	1	0	3	3	0	0	0	0
20	0	0	1	1	0	0	1	0	0	0	0	0
20.25	0	0	0	0	0	0	1	0	0	0	1	0
20.5	0	0	0	0	0	0	0	0	0	0	0	0
20.75	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
21.25	0	0	0	0	0	0	0	0	0	0	0	0
21.5	0	0	0	0	0	0	0	0	0	0	1	0
21.75	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
22.25	0	0	0	0	0	0	0	0	0	0	0	0
22.5	0	0	0	0	0	0	0	0	0	0	0	0
22.75	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
23.25	0	0	0	0	0	0	0	0	0	0	0	0
23.5	0	0	0	0	0	0	0	0	0	0	0	0
23.75	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
24.25	0	0	0	0	0	0	0	0	0	0	0	0
24.5	0	0	0	0	0	0	0	0	0	0	0	0
24.75	1	0	0	1	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0
25.25	0	0	0	0	0	0	0	0	0	0	0	0
25.5	0	0	0	0	0	0	0	0	0	0	0	0
25.75	1	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0
26.25	0	0	0	0	0	0	0	0	0	0	0	0
26.5	0	0	0	0	0	0	0	0	0	0	0	0
26.75	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0
27.25	0	0	0	0	0	0	0	0	0	0	0	0
27.5	0	0	0	0	0	0	0	0	0	0	0	0
27.75	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0

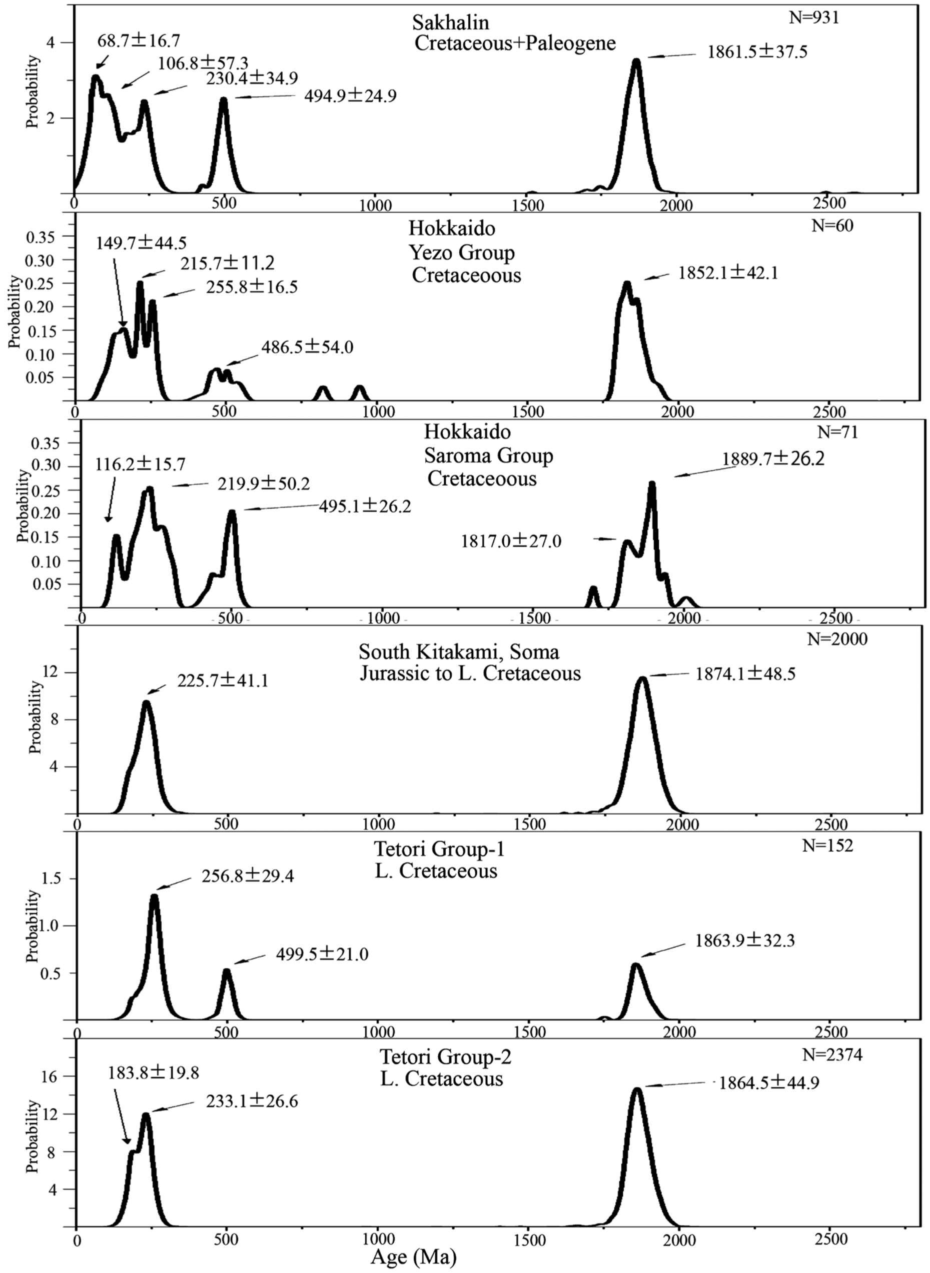

Fig. 8. Probability distribution of ages of detrital monazites in the sandstones from the non- and shallow-marine sequences in Sakhalin, Hokkaido, south Kitakami and Tetori. The numerical value (n) denotes the number of analyzed monazite grains.

sanguineous area is most common in the sandstones from the Japanese Islands. The sandstones with the bimodal pattern occur throughout the Japanese Islands from Okinawa to Hokkaido. Depositional ages of the sandstones are from the Triassic in the Mine Group, western Chugoku, to Paleogene sediments in the southwest Shimanto Belt. The Jurassic to Lower Cretaceous sandstones in the Shimokita Peninsula from the North Kitakami Belt and Cretaceous sandstones in the

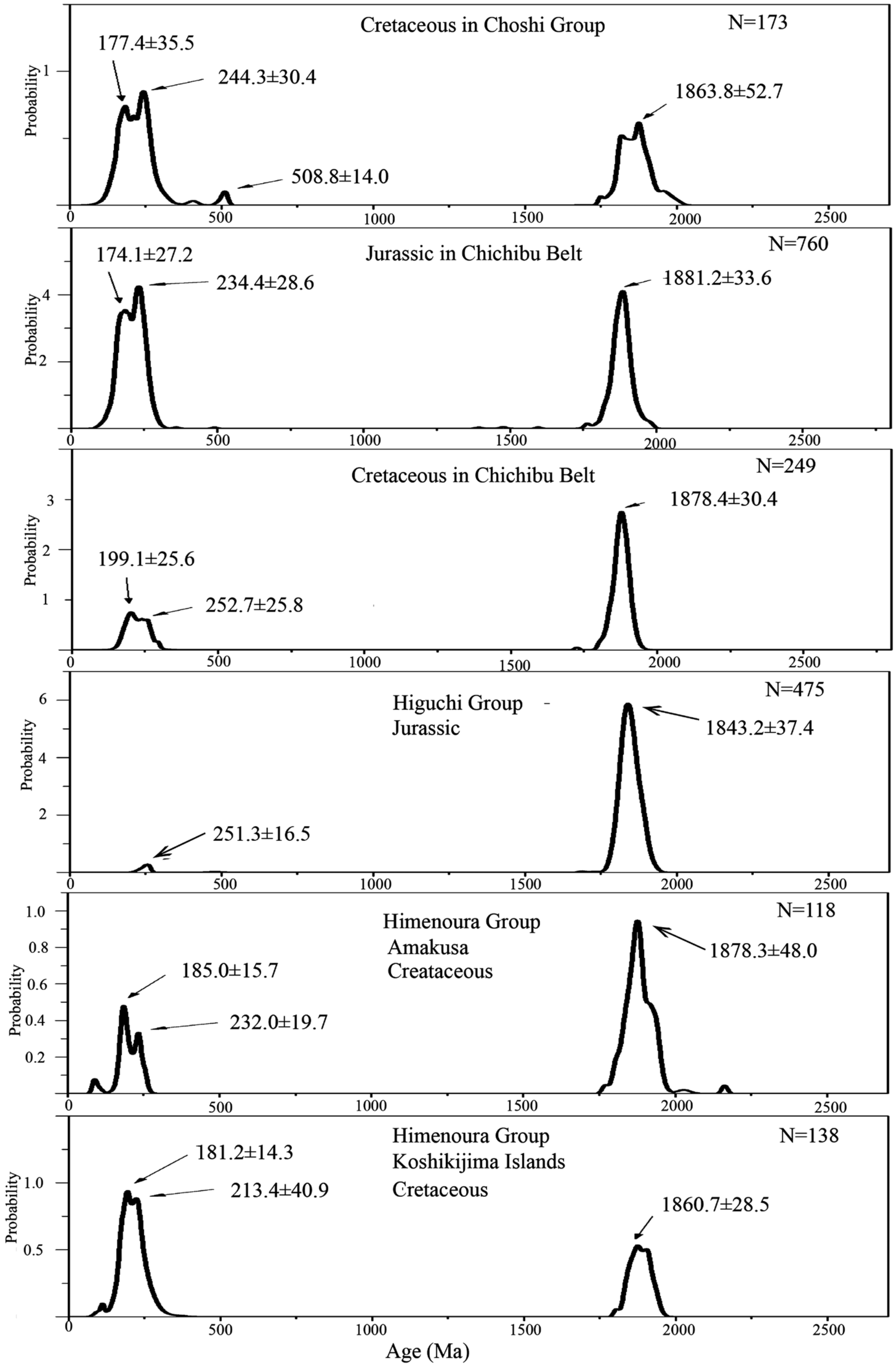

Fig. 9. Probability distribution of the ages of the detrital monazites in the Jurassic and Cretaceous sandstones from the non- and shallow-marine sequences in Chichibu Belt, Higuchi Group and Himenoura Group. The numerical value (n) denotes the number of analyzed monazite grains.

Iddonnapu Belt, Hokkaido, have also a bimodal pattern. These areas are far from the Korean Peninsula. These results show that large-scale strike slip movements occurred in the islands before the opening of the Sea of Japan. Yokoyama *et al*. (2012) concluded that Jurassic to Early Cretaceous sandstones in the Palawan microcontinental block including part of the Mindoro and Panay islands, Philippines, were parentally deposited on the eastern side of present-day Taiwan, because the sandstones are characterized by a bimodal pattern with peaks at 140–260 Ma and 1800–1950 Ma. A similar bimodal pattern is observed in the Jurassic to Cretaceous sandstones in northwest Borneo (Yokoyama *et al*., 2015). The provenance of sandstones with such a bimodal pattern is restricted from the Korean Peninsula to Wengzhou, Zhejiang Province in China, through the Qingdao area (Fig. 2: Yokoyama *et al*., 2012). The minerals in the sandstones with the bimodal pattern from the Japanese Islands, Palawan Islands and Borneo should be derived from the restricted areas mentioned above. The age pattern occasionally shows one peak at around 250 Ma or 1900 Ma, especially in the old sandstones such as Triassic Mine Group and Early Jurassic Higuchi Group. Even these cases, we tentatively use "bimodal" for the pattern.

The age pattern with a major peak at 500 Ma is observed in both the accretionary complexes and non- and shallow-marine sequences. Most of the sandstones with monazite ages of 500 Ma also have peaks at 100–300 Ma and 1850–1900 Ma similar to the sandstones with a bimodal pattern. Among the accretionary complexes, such a pattern is recognized in the Paleogene sandstones from the eastern part of the Shimanto Belt and the Jurassic sandstones in a part of the Ashio Belt. In addition to the Triassic Nabae-Yakuno Group, non- and shallow-marine sequences from Sakhalin, Hokkaido and a part of the Tetori Group also have a peak at 500 Ma. It is simply concluded that the minerals of the sandstones in these area were derived from Far-East Asia including Khanka and Jiamusi or their equivalents. Except for the Paleogene sandstones in the Shimanto Belt, this conclusion will be realistic because these areas should be close to Primorye, Far East Russia, before the opening of the Sea of Japan (e.g. Figs. 3 & 4).

The age pattern with peaks at 430–450 Ma, 700–900 Ma and 2500 Ma in addition to 200–300 Ma and 1800–1900 Ma occurs only in the Paleogene sandstones from the western part of the Shimanto Belt (Fig. 6). This pattern with complex peaks is similar to that of the Yangtze River (Fig. 7). The drainage systems of the present rivers are different from those during the Paleogene, as presented by Fan *et al.* (2004) for the Pliocene drainage basin for the paleo-Yangtze River. As the peak at 700–900 Ma is only observed from a sample from the Yangtze River, the provenance for the Paleogene sandstones included at least a part of the drainage basin of the Yangtze River. A peak at 1800–1900 Ma is much higher than that of the Yangtze River. Hence, it is probable that the provenance for the sandstones includes the Korean Peninsula. The bimodal pattern is also observed in the Paleogene sandstones from the western part of the Shimanto Belt. It may be due to the local supply that comes only from the Korean Peninsula. A tentative model for the drainage system during the Paleogene is presented in Fig. 10. The paleo-Amur River provided sands with a peak of 500 Ma to the eastern part of the accretionary complex, Shimanto Belt, whereas the paleo-Yangtze River provided sands with peaks of 400–450 Ma and 700–900 Ma to the western part of the Shimanto Belt. Kimura (1992) summarized a paleocurrent direction in the Eocene-early Oligocene Shimanto Belt. He indicated a longitudinal flow from west to east in the Okinawa–Kyushu area, whereas inverse current, i.e. from east to west, in the Kii Peninsula and eastern Shikoku. Although, the boundary between them is central part of Shikoku, his results will support the paleocurrent model in Fig. 10.

The drastic change from the bimodal pattern for the Cretaceous sandstones to the complex pattern for the Paleogene sandstones is probably due to the breakup of a barrier that divided the

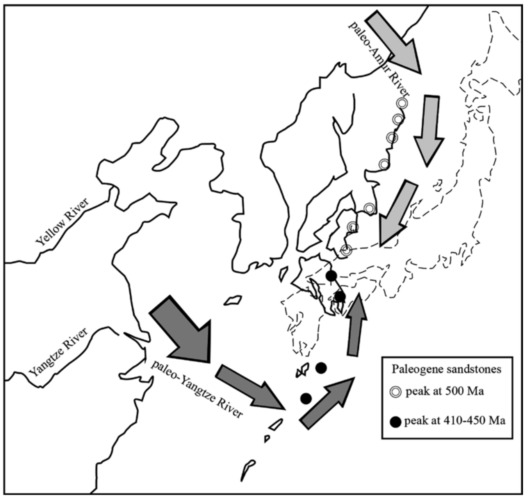

Fig. 10. Model of sediment supplies from the continent to the Paleogene accretionary complex of the Shimanto Belt.

bimodal region from the Korean Peninsula to the Fuchu area and the central part of the China Craton. From the Triassic to Cretaceous, large sedimentary basins developed in the central part of China (Wang, 1985 & 1986). They are the Ordos Basin during the Jurassic and the North China Basin during the Cretaceous. During the pre-Paleogene time, there were two drainage systems at the marginal zone of East Asia: rivers running to the northwest and to the Pacific Ocean side. After the Cretaceous, the barrier broke up and then the sediments in the central part of China started to be supplied into the continental margin and accretionary complex.

As mentioned above, the pre-Neogene sandstones in the Japanese Islands are simply divided into three types based on the age patterns of detrital monazites. This division is due to differences among the major provenances: the Korean Peninsula, Far East Russia, and central China. These divisions will contribute to the construction of a model of the Japanese Islands.

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日本列島の新第三紀以前の砂岩の供給源の研究

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日本列島の新第三紀以前の砂岩中のモナズ石の年代測定を行い，その供給源を求めた．日本の砂岩は，年代分布から大まかに3つの型に分類することができる．それらは，200 Ma前後と1850 Ma前後の2つのピークのみを持つ砂岩，ならびに，500 Ma年にピークを持つもの，400–450 Maにピークを持つものである．後者2つの型の砂岩の多くは，200 Ma前後と1850 Ma前後のピークを持つ．浅海性や非海成の砂岩は，北方や日本海沿いで500 Maのピークを持つが，その他の砂岩は，2つのピークを持つものである．深海性砂岩には，400–450 Maにピークを持つものが，九州から沖縄にかけて分布する古第三紀の四万十帯に見られる．同じ時代の四万十帯でも関東から四国の砂岩は，500 Maのピークを持つ砂岩であった．これらの供給源については，既存のアジアの河川の年代分布からほぼ特定することができた．2つのピークを持つ砂岩は，韓半島を中心にしたもので，500 Maは極東ロシア起源であり，400–450 Maは，中国中央部を起源とするものであることが判明した．