Bull. Natl. Mus. Nat. Sci., Ser. C, 41, pp. 29–43, December 22, 2015

Age distributions of monazites in the Late Cretaceous to Late Eocene turbidite from northwestern Borneo and its tectonic setting

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Abstract Late Cretaceous to Late Eocene turbidite is widely distributed in the northwestern part of Borneo. It is known as the Rajang Group. Sand samples were collected from the four rivers that flow through this stratum. More than 4000 monazite grains were analyzed by electron microprobe analyzer to obtain their ages. The monazite age distributions of the four rivers show three main peaks at 200–300 Ma, 400–500 Ma and 1850–1900 Ma, and a weak cluster at 700–1100 Ma. Such age distributions show that the detrital grains were not supplied from the Indochina Peninsula, but from the South China Craton. There is a huge unconformity, called the Sarawak Orogeny, which formed after the deposition of the Rajang Group. The Sarawak Orogeny is considered to be formed at Latest Eocene, close to the time of the opening of the South China Sea that began as early as the Early Oligocene. Hence, it is probable that the northwestern Borneo, which is situated close to South China, has been moved to its current position during the opening of the South China Sea. There is no clear tectonic event after the opening of the South China Sea between northwestern Borneo and the central part of the Indonesia Archipelago including southern Borneo. Assuming that Borneo and at least the central Indonesia Archipelago were moved at the time of the opening of the South China Sea, the reduced connection between the Indian and Pacific oceans during the Miocene and also the Wallace line for fauna and flora may be explained more simply by the present model than by the other reconstruction models.

Key words: monazite, age, Borneo, South China Sea, Rajang Group

Introduction

Southeast Asia has a complex tectonic evolutional history (Fig. 1). Many tectonic models have been presented in this area. The most outstanding models are the strike-slip model of the Ailao Shan-Red River Fault: more than 500 km left-lateral movement (e.g. Tapponnier *et al.*, 1990: Leloup *et al.*, 2001) and the opening of the South China Sea during the Oligocene to Miocene Epochs (e.g. Taylor and Hayes, 1980; Briais *et al.*, 1993). Furthermore, there are two additional models about the tectonic evolution of Borneo during the Paleogene. One describes Borneo as situated close to South China before the opening of the South China Sea (Briais *et al.*, 1993). The other model says that Borneo has not moved much from its present position and the proto-South China Sea was subducted beneath Borneo at the time of opening (e.g. Taylor and Hayes, 1980; Moss, 1998; Hall, 2002). In spite of these two models for Borneo, many authors consider that the Palawan microcontinent, northeast of Borneo, was located in the western part of Taiwan and separated from the Asian continent at the time of the opening of the South China Sea (e.g. Holloway, 1982; Hall, 2002; Yokoyama *et al.*, 2012).

The present study mainly examines the Late Cretaceous to Late Eocene sediment to study the provenance of detrital minerals on the basis of the age distribution of monazite. Many age dat-

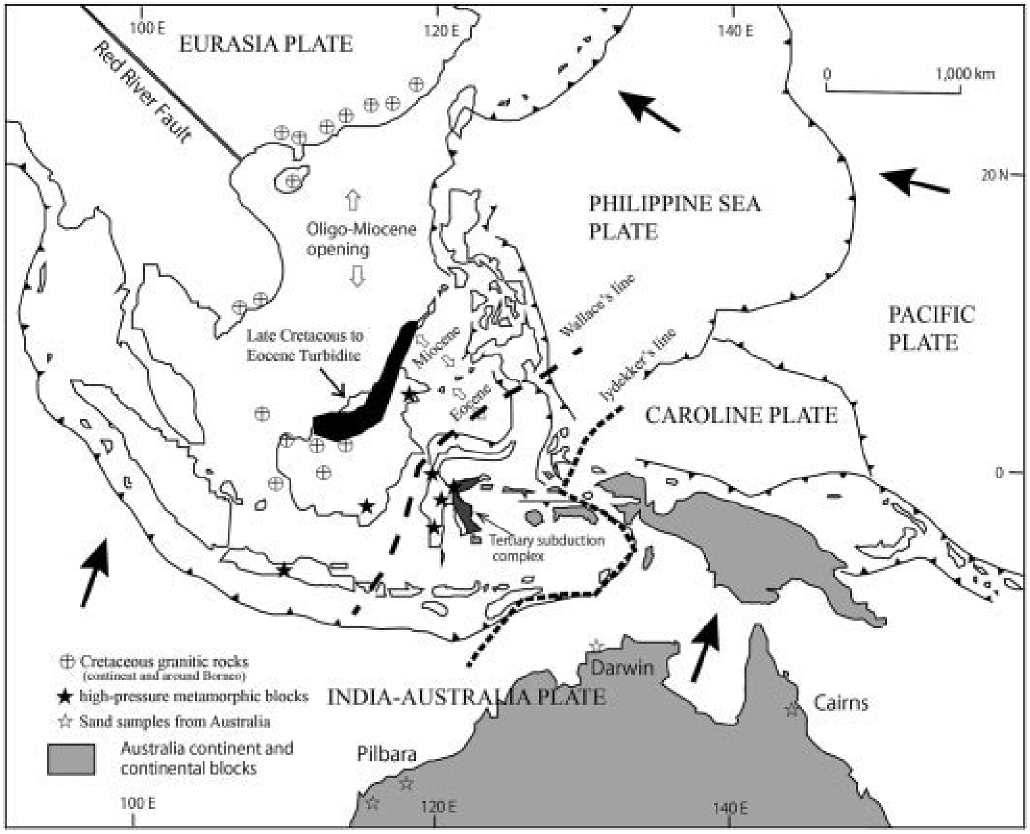

Fig. 1. Present tectonic plates in Southeast Asia. Ailao Shan-Red River shear zone, continental blocks, high-pressure metamorphic blocks, Tertiary subduction complex, Wallace's line and Lydekker's line are from Leloup *et al.* (2001), Moss and Wilson (1998) and Miyazaki *et al.* (1998).

ing methods have been applied to 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 mass spectrometry (ICP-MS) (e.g. Evans *et al.*, 2001; Wyck and 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). Because age data of monazites in the sands from the rivers cutting through the coastal provinces of Asia have already been reported (Fig. 2: Yokoyama and Tsutsumi; 2008, Yokoyama *et al.*, 2007, 2010a and 2012), the monazite age data will be a strong tool for comparison between age distribution of monazites in Borneo and those from the sands from Asia.

Geological outline and sampling sites

Hutchison (2005) summarized the regional geology of North-West Borneo, and describes that it is composed of two units. One is the Late Cretaceous to Late Eocene Turbidite sequence, Rajang Group in Sarawak, occurring from Sibu to Kota Kinabalu (Figs. 3 and 4). In Kalimantan, equivalent sediments are called as the Embaluh Group (Moss and Wilson, 1998). Hutchison (1989) and Moss and Wilson (1998) have suggested that a proto-Mekong river system fed the Rajang-Embaluh Group basin. Along the northern coast, Oligocene to Miocene sediments, mostly limestones, occur and there is drastic dis-

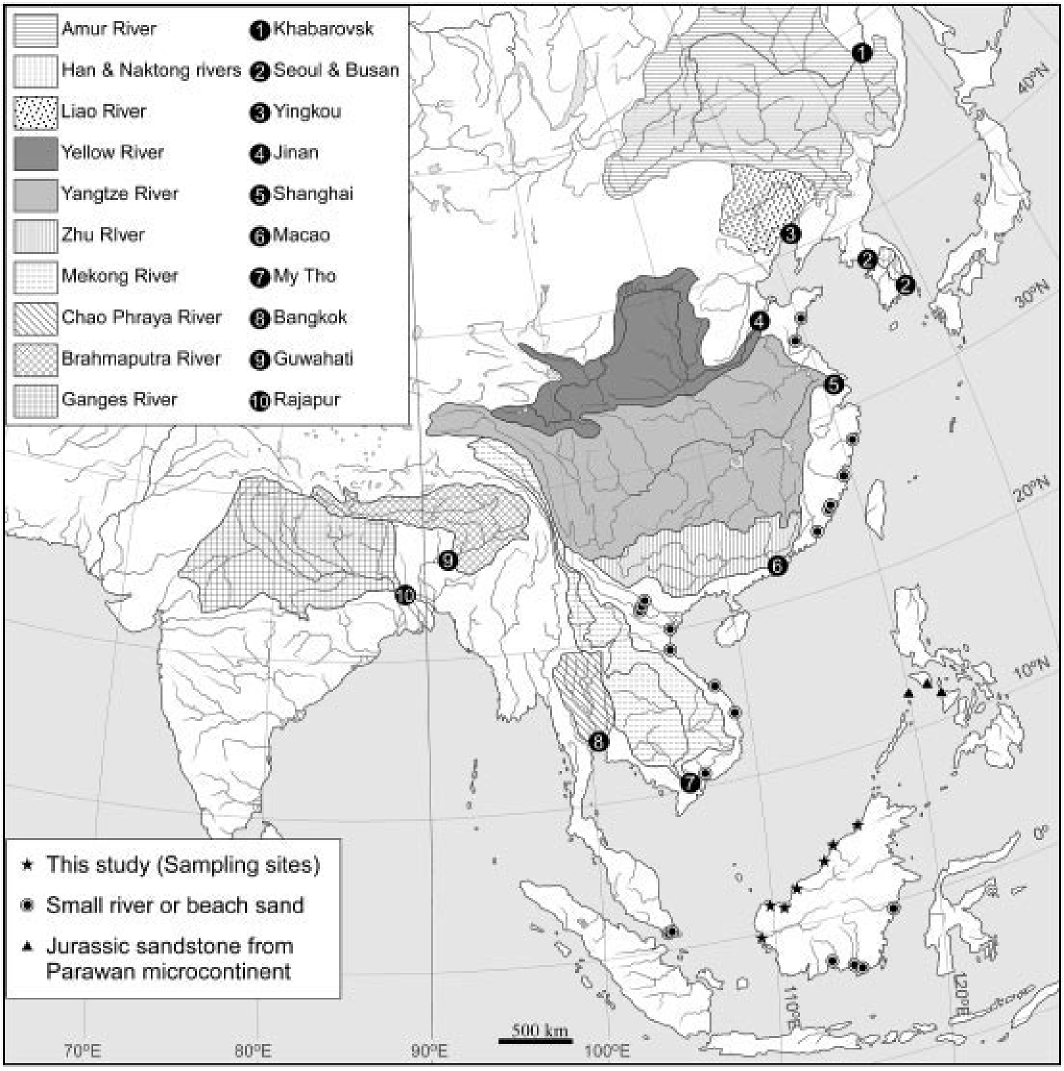

Fig. 2. Sampling localities of sands from the rivers in northwest Borneo. The sampling sites from Asia where age data had been published are shown here (Yokoyama *et al.*, 2007, 2008, 2010a, b and 2012)

continuity, so-called Sarawak Orogeny, between the Rajang Group and the Oligocene-Miocene sediments (Fig. 3). The other unit is the Kuching Zone on the western end of northwestern Borneo. The zone contacts with the Rajang Group by the Lupar Line and consists of various rocks such as Carboniferous to Permian rocks, Jurassic-Cretaceous shelf deposits and metamorphosed subduction complex and Paleocene to Oligocene fluvial to deltaic deposit (Fig. 3). In this zone, Triassic plant fossils, consisting of Krusin flora, are closely comparable to the Tonkin flora of northern Vietnam, and the Triassic volcanic rocks are comparable to the Kontum Massif in the central Vietnam. A Jagoi granodiorite body occurs in the Jurassic-Cretaceous terrane. Its K-Ar age is 195 Ma, but the age is thought to have resulted from argon loss. There are many igneous intrusives in the zone. They are granitic rocks and diorite with ages from the Cretaceous to the Miocene.

The samples including detrital minerals were collected only from river sands in all of the areas (Fig. 4). Four samples were collected from rivers

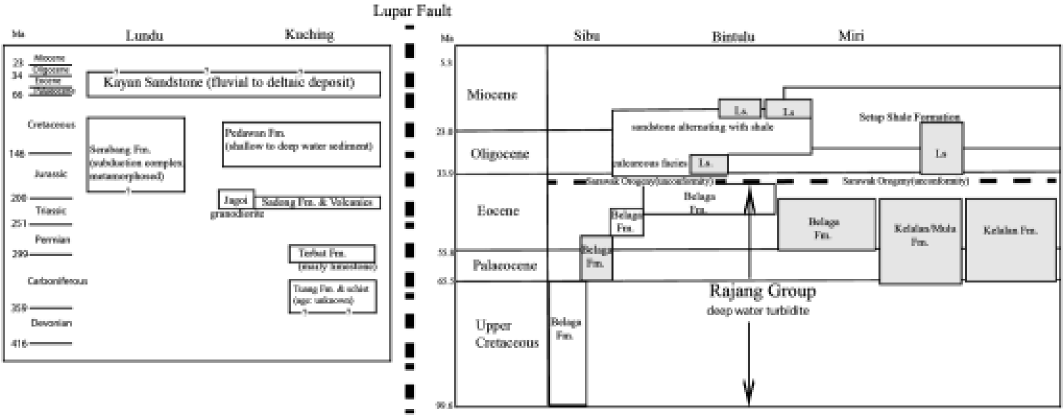

Fig. 3. Stratigraphy of the major formations of the Kuching and Sibu-Miri zones (after Hutchison, 2005).

cutting through the Late Cretaceous to Late Eocene formation, the Rajang Group, at Sibu, Bintulu, Miri and Kota Kinabalu (Fig. 4). Among the four rivers, the Rajang River in Sibu has a huge drainage basin. Likas and Kemena rivers from Kota Kinabalu and Bintulu, respectively, have small drainage basins. The Likas River is cutting through the West Crocker Formation where the few microfossils are not age-diagnostic within the Eocene to Miocene (Hutchison, 2005). The formation is probably Eocene in age (Lambiase *et al.*, 2008), differing from the generally accepted Eocene or Oligocene to early Miocene. As discussed later, the age distribution for the Likas River is not different from the other major rivers. Here, we tentatively accept that the West Crocker Formation is a part of the Rajang Group as far as the small drainage basin of the Likas River is concerned.

Two samples were collected from the rivers in the Kuching zone. They are the Kayan and Sarawak rivers with small drainage basins cutting mainly through the Kayan Sandstone and the Pedawan Formation, respectively (Fig. 5). In addition to limestone from the Terbat Formation, monazite is not present or not preserved in metamorphic rocks such as the Serabang Formation, Tuang Formation and Kerait schist. Among the constituents in the Kuching zone, the probable provenance of monazite is the Pedawan Formation and Kayan Sandstones. There are many granitic intrusives from Cretaceous to Miocene in age (Hutchison, 2005). They are also probable sources of monazite. One sand sample was collected from the Kapuas River, Pontianak of Kalimantan. The drainage basin of the river partly includes constituents from the Kuching and Sibu zones, but is composed mostly of Cretaceous granitic rocks of the Schwaner Mountains.

Many river sands have been collected from East Asia as shown in Fig. 2 and age data have already been published (Yokoyama and Tsutsumi, 2008; Yokoyama *et al.*, 2007, 2010a, b, 2012). Drainage basins of the rivers are probable candidates for the sedimentary rocks of northwestern Borneo. Placer diamond deposits without any obvious local or regional diamond source occur in southwest Borneo. Metcalfe (2009) considered that southwest Borneo is possibly a continental block separated from northwest Australia where many diamond mines operate. So, as additional data, we collected sands from four rivers on the Australian Continent as shown in Fig. 1.

Analytical Procedures

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

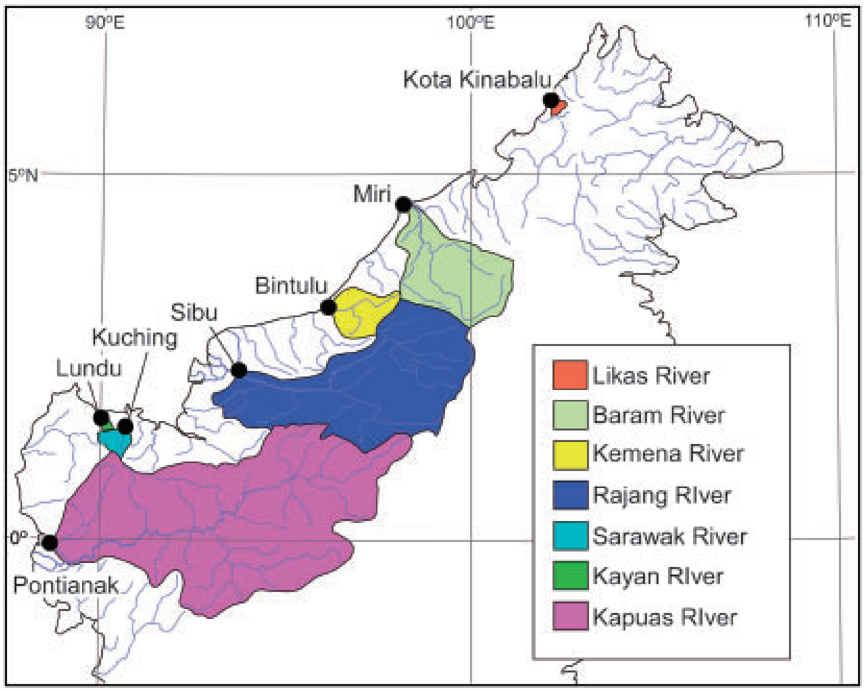

Fig. 4. Drainage systems of rivers in northwestern Borneo and sampling sites (black circles).

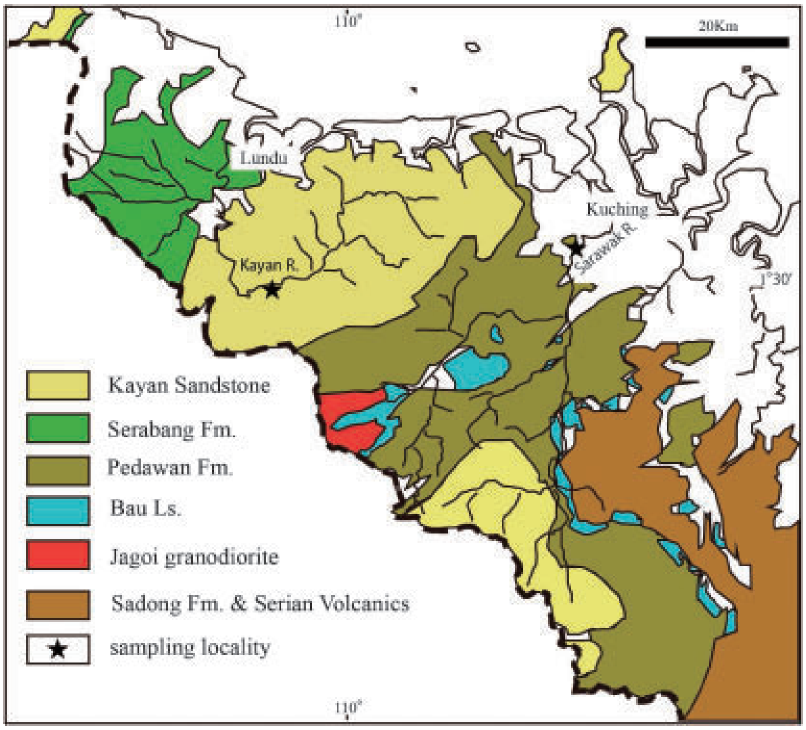

Fig. 5. Simplified geology of the Kuching zone. Stratigraphic relation of all the formations in the Kuching zone is shown in Fig. 3.

electron probe micro-analyzer, EPMA, fitted with a Wavelength Dispersive Spectrometer (WDS), JXA-8800 situated in the National Museum of Nature and Science. Analytical conditions have been described by Santosh *et al.* (2003). Age calibrations were carefully performed by comparing data obtained by EPMA dating with those acquired by the SHRIMP technique (e.g. Santosh *et al.*, 2006). Apart from minor shifts due to machine drift and variations 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.

Age of Monazite

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. 300 Ma) or less than 25 Ma in younger monazites (<ca. 300 Ma). If a doubtful age was obtained, age analyses were repeated and one representative age has been selected from each grain.

About 4000 monazite grains have been analyzed from the river sands from Borneo and the Australian Continent. All the age data are summarized in Table 1. Age distributions of monazites from the rivers in Borneo and Australia are presented as probability diagrams in Figs. 6 and 7. Probability distributions for monazite ages were calculated with a multi-peak Gauss fitting method (Williams, 1998).

The monazite ages of the sands from four rivers cutting through Rajang Group range from ca. 0 Ma to 3000 Ma with strong populations at 200–300 Ma, 400–500 Ma and 1800–2000 Ma. Small peaks are found at around 900 Ma. Monazite with ages greater than 2000 Ma is rare. The oldest monazite grain is 3036 ± 17 Ma from Sibu (Fig. 8). Roughly speaking, the four river sands have a similar age distribution pattern showing that they were derived from a similar drainage basin, i.e. Rajang Group. Relatively strong peaks are observed at ca. 110 Ma from Sibu and at 40 Ma from Miri. The former is probably due to contribution from Cretaceous granitic rocks in the Rajang Group area (Hutchison, 2005). The latter young age is due to local intrusions of Eocene Bukit Piring granodiorite in the drainage basin (Hutchison, 2005). Although the Likas River from Kota Kinabalu has a drainage basin consisting of the West Crocker Formation, there is no critical difference in the age distributions from the other three rivers.

On the other hand, the age distributions of the river sands from Kuching and Pontianak areas are different from those mentioned above. The Sarawak River with drainage basin from the Jurassic to Cretaceous Pedawan Formation has a strong peak at 50 Ma and small peaks at 210 and 1850 Ma. The Kayan River cutting through mostly Paleogene sediment has peaks at 29 Ma and 210 Ma. The Kapuas River in Pontianak with a drainage basin mainly of granitic rocks has a strong peak at 110 Ma. Peaks at around 430 Ma and 900 Ma, which are observed in the rivers from Sibu and its eastern part, are negligible in the Kuching and Pontianak areas.

Age data from the Australian Continent are shown in Fig. 7. Two rivers, Maitland and Sharlook, from the Pilbara area have a strong peak at 3000 Ma. Age data from Darwin have strong peaks at 1800 Ma, 610 Ma and 280 Ma. On the other hand, age distribution from the Barron River, Cairns, has only one peak at 305 Ma. As these age data are totally different from those from Borneo, the continent is not a candidate for the provenance of the sediments in Borneo. The Australian Continent is now close to Borneo, but it was far from Borneo at the depositional time of

Table 1. Age data of monazite in the sands from Sarawak, Borneo, and northern Australia. Each number shows a monazite grain analysed. Age in table shows a range of age, i.e. 0 ranging from 0 Ma to 25 Ma and 5 ranging 500 Ma to 525 Ma.

Age	Sarawaku, Borneo							Australia			
	Sibu	Miri	Bintulu	Kota Kinabalu	Pontianak	Kuching	Lundu	Ma R.	Sha R.	Darwin	Cairns
0	5	12	3	0	0	60	240	0	0	0	0
0.25	5	32	8	0	11	91	195	0	0	0	0
0.5	15	13	8	0	12	81	66	0	0	1	0
0.75	66	5	2	0	42	29	27	0	0	2	0
1	70	9	8	2	91	12	29	0	0	0	0
1.25	40	9	4	1	61	6	19	0	0	1	0
1.5	26	11	5	6	15	7	14	0	0	0	0
1.75	27	8	7	11	4	12	54	0	0	0	0
2	104	22	17	9	13	22	78	0	0	1	0
2.25	190	45	36	13	7	14	62	0	0	2	0
2.5	81	18	21	39	1	5	11	0	0	18	10
2.75	7	6	7	24	1	1	2	0	0	30	51
3	3	1	1	12	0	0	10	0	0	9	59
3.25	6	2	0	2	0	6	4	0	0	1	33
3.5	5	2	1	3	0	2	2	0	0	0	5
3.75	8	4	2	0	0	0	2	0	0	2	0
4	47	2	4	0	2	4	1	0	0	7	0
4.25	56	10	14	8	2	1	2	0	0	11	0
4.5	31	15	8	11	1	2	3	0	0	6	0
4.75	18	4	1	4	1	1	2	0	0	5	0
5	22	1	0	0	1	0	2	0	0	4	0
5.25	19	1	0	2	0	1	5	0	0	9	0
5.5	10	0	0	5	1	1	1	0	0	8	0
5.75	4	0	0	0	1	1	3	0	0	14	0
6	2	0	0	0	0	0	2	0	0	25	0
6.25	2	0	0	0	0	0	1	0	0	8	0
6.5	0	0	0	0	0	1	0	0	0	3	0
6.75	0	0	0	0	0	0	0	0	0	1	0
7	0	0	0	0	0	0	1	0	0	0	0
7.25	0	0	0	0	0	0	0	0	0	1	0
7.5	0	0	0	0	0	0	0	0	0	0	0
7.75	3	1	0	0	0	0	1	0	0	0	0
8	2	1	0	0	0	0	0	0	0	0	0
8.25	2	0	0	0	0	0	0	0	0	0	0
8.5	0	0	1	0	0	0	0	0	0	0	0
8.75	2	0	0	0	0	0	0	0	0	0	0
9	6	1	0	0	0	0	1	0	0	0	0
9.25	13	0	1	2	0	1	1	0	0	1	0
9.5	7	1	0	2	0	0	1	0	0	0	0
9.75	2	0	0	0	0	3	2	0	0	0	0
10	5	0	0	0	0	0	2	0	0	0	0
10.25	3	0	1	0	0	0	0	0	0	0	0
10.5	6	1	0	0	0	0	0	0	0	0	0
10.75	2	2	0	0	1	1	1	0	0	0	0
11	2	0	1	0	0	0	4	0	0	0	0
11.25	0	0	0	0	0	0	0	0	0	2	0
11.5	1	1	0	0	0	0	0	0	0	1	0
11.75	1	0	0	0	0	0	0	0	0	0	0
12	2	0	0	0	0	1	0	0	0	0	0
12.25	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	1	0
12.75	0	0	0	0	0	0	0	0	0	0	0
13	1	0	0	0	0	0	0	0	0	0	0
13.25	0	0	0	0	0	0	0	0	0	0	0
13.5	0	0	0	0	0	0	0	0	0	0	0
13.75	1	0	0	0	0	0	0	0	0	0	0
14	1	0	0	2	0	0	0	0	0	0	0
14.25	0	0	0	2	0	0	0	0	0	0	0
14.5	0	0	0	0	0	0	0	0	0	0	0
14.75	1	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0
15.25	3	0	0	0	0	0	1	0	0	3	0
15.5	1	0	0	0	0	0	0	0	0	5	0
15.75	0	0	0	0	0	1	0	0	0	9	2

Table 1. (continued)

Age	Sarawaku, Borneo							Australia			
	Sibu	Miri	Bintulu	Kota Kinabalu	Pontianak	Kuching	Lundu	Ma R.	Sha R.	Darwin	Cairns
16	1	0	0	0	0	0	0	0	0	3	1
16.25	0	0	0	0	0	0	0	0	0	3	0
16.5	1	0	0	0	0	0	0	0	0	1	0
16.75	0	0	0	0	0	0	0	0	0	3	0
17	0	0	0	0	0	0	0	0	0	5	0
17.25	2	0	0	0	1	0	0	0	0	23	0
17.5	4	1	2	0	0	0	0	0	0	29	0
17.75	1	2	2	0	2	0	0	0	0	49	0
18	20	2	3	2	0	2	0	0	0	54	0
18.25	20	12	3	0	1	8	1	0	0	45	0
18.5	28	4	1	2	0	9	1	0	0	25	0
18.75	10	2	0	4	1	12	0	0	0	11	0
19	5	0	1	4	0	6	2	0	0	8	0
19.25	1	0	0	0	0	3	2	0	0	2	0
19.5	0	0	0	0	0	0	0	0	0	0	0
19.75	0	0	0	0	0	0	1	0	0	0	0
20	0	1	0	0	0	0	0	0	0	0	0
20.25	0	0	0	0	0	0	0	0	0	0	0
20.5	1	0	0	0	0	0	0	0	0	1	0
20.75	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0
21.25	0	0	0	0	0	0	0	0	0	0	0
21.5	0	0	0	0	0	0	0	0	0	0	0
21.75	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0
22.25	0	0	0	0	0	0	0	0	0	0	0
22.5	0	1	0	0	0	0	0	0	0	0	0
22.75	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0
23.25	0	0	0	0	0	0	2	0	0	0	0
23.5	1	0	0	0	0	0	0	0	0	0	0
23.75	1	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	1	0	0	0	0
24.25	0	1	0	0	0	0	0	0	0	0	0
24.5	1	0	0	0	0	1	0	0	0	0	0
24.75	1	0	0	0	0	0	0	0	0	0	0
25	2	0	0	0	0	1	0	0	0	0	0
25.25	0	0	0	0	0	0	0	0	0	0	0
25.5	0	1	0	0	0	0	0	0	0	0	0
25.75	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0
26.25	2	0	0	0	0	0	0	0	0	0	0
26.5	0	0	0	0	0	0	0	0	0	0	0
26.75	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	1	0	0	0	0
27.25	0	0	0	0	0	0	0	0	0	0	0
27.5	0	0	0	0	0	0	0	0	0	0	0
27.75	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0
28.25	0	0	0	0	0	0	0	0	0	0	0
28.5	0	0	0	0	0	0	0	0	0	0	0
28.75	0	0	0	0	0	0	0	0	1	0	0
29	0	0	0	0	0	0	0	1	5	0	0
29.25	0	0	0	0	0	0	0	0	9	0	0
29.5	0	0	0	0	0	0	0	9	41	0	0
29.75	0	0	0	0	0	0	0	15	28	0	0
30	1	0	0	0	0	0	0	10	12	0	0
30.25	0	0	0	0	0	0	0	8	6	0	0
30.5	0	0	0	0	0	0	0	2	4	0	0
30.75	0	0	0	0	0	0	0	1	0	0	0
31	0	0	0	0	0	0	0	0	1	0	0
31.25	0	0	0	0	0	0	0	2	2	0	0
31.5	0	0	0	0	0	0	0	0	1	0	0
31.75	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	1	0	0
total gr.	1039	267	173	172	273	409	863	48	111	453	161

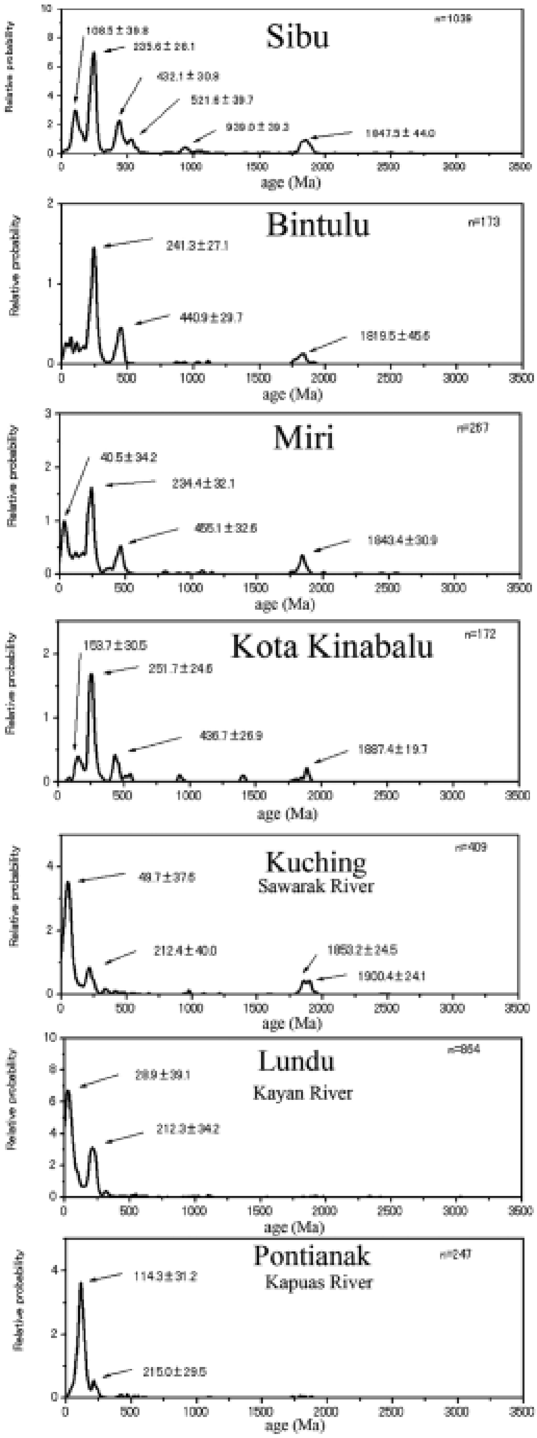

Fig. 6. Probability distribution diagrams of monazite ages in the sand samples from Borneo. Numerical value (n) denotes the number of analyzed monazite grains.

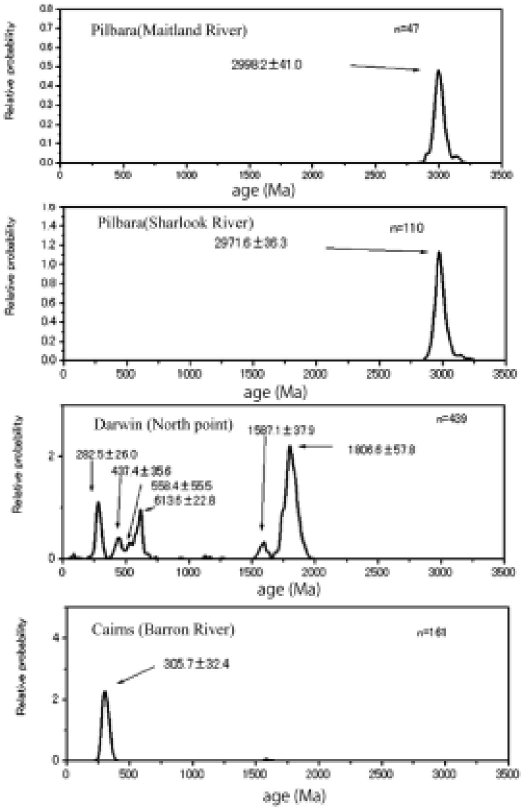

Fig. 7. Probability distribution diagrams of monazite ages in the sand samples collected from the northern part of the Australian Continent. Localities are shown in Fig. 1.

the Rajang Formation and the other formations. Hence, there is no more discussion here about the age data from the Australian Continent.

Monazite ages in the sands collected from major rivers in Asian are reproduced in Fig. 9 (after Yokoyama *et al.*, 2010b). Each river sample has its distinct age distribution characteristics, reflecting the different rocks within their drainage basins. In the Korean Peninsula, monazite ages show a clear bimodal pattern with clusters at 100–300 Ma and 1800–2000 Ma, and monazite with ages from 300 Ma to 1800 Ma is scarce. A similar bimodal pattern is observed for the sands collected from South and North China: Qingdao and Zhejiang (Yokoyama *et al.*, 2012). The Jurassic to Early Cretaceous subduction complex from the Busuanga Island, northeast

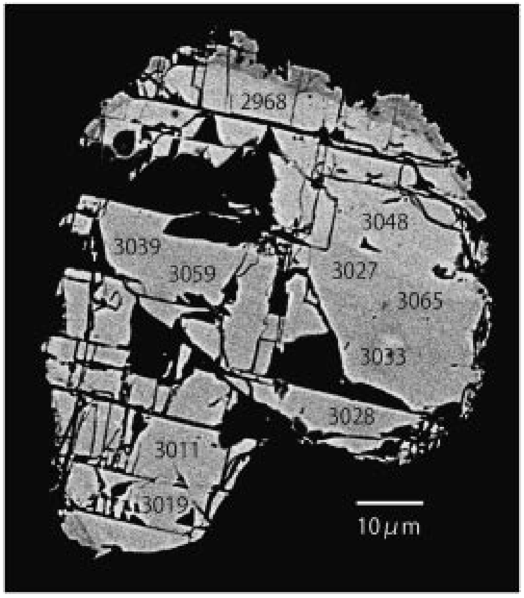

Fig. 8. The oldest monazite grain found from Sibu. Numbers in the grain are age shown as Ma. Obtained age is 3036 ± 17 Ma.

Palawan, also has a bimodal pattern, similar to those mentioned above. Yokoyama *et al.* (2012) concluded that the Palawan microcontinent was located southwest of present-day Taiwan before the opening of the South China Sea, but Jurassic to Early Cretaceous sandstones were parentally deposited on the eastern side of present-day Taiwan.

Both the Yellow and Yangtze rivers have huge drainage basins. Sands from both rivers have monazite age peaks at 100–300 Ma, 410 Ma and ca.1900 Ma. The strongest peak appears at 0–25 Ma for the Yangtze River (Fig. 9). The young monazites were almost certainly derived from the Himalayan region where it 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 of the Rajang Group in Borneo. A cluster between 700 and 1000 Ma in

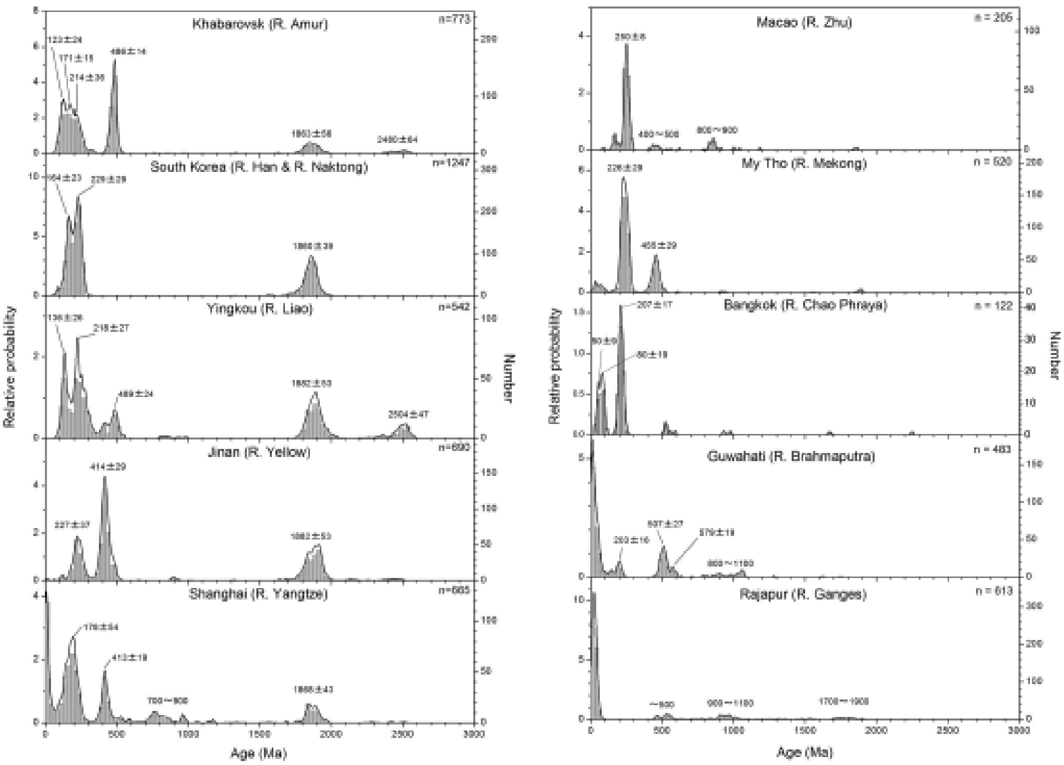

Fig. 9. Probability distribution diagrams of monazite ages in the sands from major rivers in East Asia. Sampling localities of the major rivers are shown in Fig. 2.

the age pattern of the Yangtze River is relatively high and is representative of the Yangtze 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 450 Ma peak in the Pliocene sand to 410 Ma in Recent sand (Fan *et al.*, 2004).

The sand sample from the Zhu River (Fig. 9) that flows through the Guangxi and Guangdong provinces has a different monazite age distribution pattern compared with the other samples. It has a strong peak at 250 Ma and very weak peaks at 400–500 Ma and 800–900 Ma. No clear peak at 1900 Ma has been recognized in the sand from the Zhu River. The Mekong River has two major peaks at 230 Ma and 460 Ma. Monazite older than 500 Ma is scarce. These characteristics are similar to small rivers from Vietnam (Yokoyama *et al.*, 2010a). The Chao Phraya River from Bangkok has strong peaks at around 70 Ma and 210 Ma. A small peak at 500–600 Ma is observed, but older monazite is scarce. Both the Ganges and Brahmaputra rivers have a strong peak at 0–25 Ma, clearly Himalaya in origin, similar to that from the Yangtze River. The data from India including those from the Amur River are not important when we discuss the provenance of the detrital monazites in Borneo.

Discussion

The opening of the South China Sea needs to be taken into account when comparing the monazites from the river and/or beach sands with those in the Rajang Group in Borneo. The East Asian continent has been stable at least since the end of the Cretaceous (cf. Lee and Lawver, 1995), and the sediments of the Rajang Group have been derived from the Asian Continent including the South China Craton and Indochina Peninsula. Hence, it is useful to consider monazite age distribution data from modern river systems as an analogue for those in the sediment of the Rajang Group.

Some authors considered that the proto-South China Sea was subducted beneath Borneo at the time of the opening of the South China Sea (e.g. Taylor and Hayes, 1980; Hall, 2002). As an explanation of the provenance of the detrital minerals in the Late Cretaceous to Late Eocene turbidite, the Rajang Group, it was considered that detrital minerals were derived from the Indochina Peninsula. The monazite age distributions of the Rajang Group show three main peaks at 200–300 Ma, 400–500 Ma and 1850–1900 Ma, and a weak cluster at 700–1100 Ma. Age data from the major and small rivers at the Indochina Peninsula had been published already (Yokoyama and Tsutsumi, 2008; Yokoyama *et al.*, 2010b). We first compare the data from the Indochina Peninsula and Rajang Group. The distinct difference is the presence of a peak at 1900 Ma from the Rajang Group and the scarcity of age data at the peak from the peninsula. Peaks around 700–1000 Ma are also present from the Rajang Group and are absent from the peninsula, showing that sediments of the Rajang Group were not supplied from the peninsula.

A peak at 1900 Ma is observed from the Yangtze and Yellow rivers (Fig. 9) and is a strongest peak from the Korean Peninsula and Liao rivers. Hence, it is probable that at least the drainage basins of the Yangtze and Yellow rivers or their more eastern areas are candidates for the provenance of the Rajang Group sediments. Other main peaks are 230–250 Ma and 430 Ma from the Rajang Group. The Zhu River sample from Macao has a strong peak at 250 Ma. The present and Latest Cenozoic sands from the Yangtze River have 410 and 450 Ma peaks, respectively (Fan *et al.*, 2004). So, if we roughly compare the age data, it is reasonable to conclude that the sediments of the Rajang Group were derived from drainage basins of the Yangtze and Zhu rivers. This is supported by the presence of peaks at 700–1000 Ma that are present in both the Yangtze and Zhu rivers. Drainage basins of the Yellow and Liao rivers and Korean Peninsula are excluded from provenance candidate for the Rajang Group sediment, because there is not a peak at 700–1000 Ma. The oldest monazite is

3000 Ma from the sample in Sibu (Fig. 8). Such an age has not been reported from the Indochina Peninsula but found from the South China Craton (Qiu *et al.*, 2000: Zhang *et al.*, 2006).

Hattum *et al.* (2006) obtained various peaks from age distributions through detrital zircons in the Crocker Formation using sensitive high-resolution ion microprobe. Their age range was from 50 Ma to 2530 Ma. Age distribution of monazite is usually simpler than that of zircon, because there is a restricted source for the monazite: granitic and high-grade metamorphic rocks. Even though there are many peaks in their results and no detailed zircon datum from the Malay Peninsula, the authors concluded that provenances of the detrital minerals were derived from the Schwanar Mountains and Tin Belt, Malay Peninsula: Cretaceous peak from Schwanar and Paleoproterozoic peak at around 1800 Ma from the Malay Peninsula. The present result shows that monazites from Kota Kinabalu, as well as those from the other areas in the Rajang Group, are also parentally derived from South China. As an alternative idea, it is possible that the detrital minerals from the West Crocker Formation were reworked from the Rajang Group.

According to the plate tectonic reconstruction before the opening of the South China Sea, Briais *et al.* (1993) set Borneo close to the coastal area of South China. Their model supports that the Paleogene sediments in Borneo were derived from South China. In spite of the acceptance of the opening of the South China Sea, Taylor and Hayes (1980) and Hall (1998 and 2002) set the proto-South China Sea between South China and Borneo. As far as the proto-South China Sea was concerned, reconstruction models indicate that provenance of the Rajang Group sediments was from the Indochina Peninsula. We conclude that the proto-South China Sea was not present before the opening of the South China Sea and turbidite sediments were directly derived from the drainage basins of present Yangtze and Zhu rivers as shown in the reconstruction model (Fig. 10). Schmidtke *et al.* (1990) and Fuller *et al.* (1999) indicated anticlockwise rotation of many

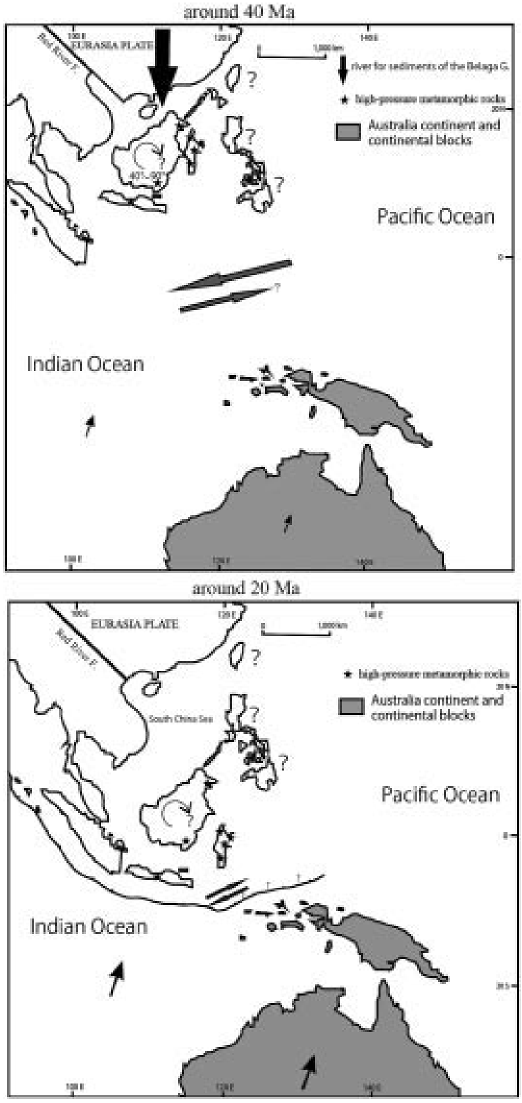

Fig. 10. Reconstruction models of Southeast Asia at around 40 and 20 Ma. Anticlockwise rotation by Schmidtke *et al.* (1990) and Fuller *et al.* (1999) has not been considered in the figures. A certain degree of rotation of Borneo will connect the Cretaceous granitic blocks in the continent and Borneo. Positions of plate subductions, Philippine and Taiwan islands have not been considered in the models.

formations in the Kuching area with various degrees of rotation. The reconstruction model in Fig. 10 does not take the rotation in consideration, because the mechanism for the anti-clockwise rotation remains enigmatic as suggested by

Hutchison (2005). Positions of plate subductions, including those for the Philippine and Taiwan islands have not been considered heve due to our poor knowledge. In this model (Fig. 10), Borneo was reset closer to South China than the model by Briais *et al.* (1993). The present South China Sea consists of oceanic crust and highly attenuated continental crust (e.g. Hutchison, 2005). Briais *et al.* (1993) only considered the area of the oceanic crust for their reconstruction. On the other hand, our rough model is based on the assumption that continental crust with a normal thickness was highly attenuated into strongly thinned crust during the opening of the South China Sea.

There is a huge unconformity, the so-called Sarawak Orogeny, that occurred after the deposition of the Rajang Group (Fig. 3). The Sarawak Orogeny is Latest Eocene in age, which is close to when the opening of the South China Sea started during the Early Oligocene (Briais *et al.*, 1993). The unconformity is explained by the model that northern Borneo, located close to South China, had been moved to its current position during the opening of the South China Sea (Fig. 10) and there was no more supply of clastic sediment from South China to produce an unconformity.

There is no clear tectonic event after the opening of the South China Sea between the northern Borneo and the central Indonesia Archipelago including southern Borneo. Unfortunately the geology of the Indonesia Archipelago is poorly known, mostly due to a wide covering of Quaternary volcanics and sediments. There are outcrops of Cretaceous high-pressure metamorphic blocks and granitic rocks sporadically throughout the archipelago (Parkinson *et al.*, 1998; Miyazaki *et al.*, 1998). Assuming that Borneo and the central Indonesia Archipelago were moved together at the time of the opening of the South China Sea, the plate subduction will occur at the boundary between the Australian Continent and the Indonesia Archipelago. The high-pressure metamorphic rocks and ophiolite occurring at the central part of the Celebes (Miyazaki *et al.*, 1998; Moss and Wilson, 1998) may be a product of the subduction at the time of the opening of the South China Sea (Fig. 1). The metamorphic age of 28–32 Ma (*cf.* Moss and Wilson, 1998) is probably related to the opening of the South China Sea from 32 Ma to 16 Ma. The subduction zone is similar to the Wallace line for fauna and flora. Kennett *et al.* (1985) studied planktonic species between Indian and Pacific oceans and found a change at around 20 Ma. Collision of the Indochina Archipelago and Australian Continent closed the deep-water passage between Pacific and Indian oceans and there must have been major changes in oceanic currents by about 20 Ma (Hall, 1998). The Wallace line for fauna and flora may be explained more simply by the opening of the South China Sea than by the other reconstruction models. The tectonic models by Hall (2002) and Moss and Wilson (1998) show that Borneo and the Indochina Archipelago were set more closely to the Australian Continent during the Eocene, which is different from our model where the Australian Continent and the Indochina blocks are far apart from each other at the time of the opening of the South China Sea. The Kuroshio Current is now running from the western Pacific towards the Japanese Islands through Taiwan. Its current or proto-Kuroshio Current may be strengthened after the reduced connection of the two oceans and also may be related to the opening of the South China Sea.

NE–SW structures of the Cretaceous granitic belt in South China disappear against the Red River Fault and Cretaceous granitic rocks appear at the southern end of Vietnam (*cf.* Leloup *et al.*, 2001). Cretaceous granitic rocks occur in the Kuching zone and its northwestern part, in addition to the Shwaner Mountains which is a major part of the drainage basin of the Kapuas River (Hutchison, 2005). If Borneo was close to South China as shown in Fig. 10 and anti-clockwise rotation had been taking place more or less before Borneo achieved its present orientation (Fuller *et al.*, 1999), the Cretaceous granitic rocks in Borneo may cover the disconnection of the granitic belt.

Geology of the Kuching zone is very complex (Hutchison, 2005). As the present age study in the Kuching zone is restricted to two rivers, more age data will be necessary to discuss the provenance of detrital monazites. However, some comments are presented here for future work. The Kayan River has a drainage basin mainly of Oligocene sediment. The age peaks are 29 Ma and 210 Ma. The former age is derived probably from the intruded igneous rocks after deposition of the Kayan sediment. The latter age, 210 Ma, will be the Jagoi granodiorite occurring at the Kuching zone. So far, there is no clear connection between the Kuching zone and the Indochina Peninsula and/or South China. On the other hand, the Sarawak River cutting through Jurassic-Cretaceous rocks and Paleogene formation has three peaks at 50 Ma, 212 Ma, and 1800–1950 Ma. The former two young peaks may be explained by local igneous rocks occurring in or around the Jurassic rocks. Yokoyama *et al.* (2012) concluded that Jurassic to Early Cretaceous sandstones in the Parawan 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 bimodal peaks; at 140–260 Ma and 1800–2000 Ma. Although the age data of the Kuching zone are not enough and still enigmatic, the 1800–1950 Ma peak from the Sarawak River may be related with South China or far eastern areas as well as the Parawan Jurassic-Cretaceous subduction complex.

Acknowledgements

The authors are very grateful to Ms. M. Shigeoka for her help with modal and chemical analyses and the heavy mineral separations throughout this study.

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