国立科博専報，(48), pp. 177–199, 2012 年 3 月 28 日
Mem. Natl. Mus. Nat. Sci., Tokyo, (48), pp. 177–199, March 28, 2012

Provenance Study of Jurassic to Early Cretaceous Sandstones from the Palawan Microcontinental Block, Philippines

Kazumi Yokoyama[1,*], **Yukuyasu Tsutsumi**[1], **Tomoki Kase**[1], **Karlo L. Queaño**[2] **and Aguilar Yolanda M.**[2]

[1] Department of Geology, National Museum of Nature and Science, Tokyo, 4–1–1 Amakubo, Tsukuba, Ibaraki 305–0005, Japan
[2] Mines and Geosciences Bureau, Diliman, Quezon City, Philippines
* E-mail: yokoyama@kahaku.go.jp

Abstract. The Palawan microcontinental block in the Philippines was separated from the southwestern coast of the Asian continent (i.e. southwestern Taiwan) during the opening of the South China Sea in the Oligocene to Miocene times. In this paper, provenances of the detrital grains in the Jurassic to Early Cretaceous sandstones from the Palawan block were studied to determine whether they were derived from the Asian continent. Age distributions of detrital monazites in the sandstones from the Busuanga, Mindoro, and Panay islands are essentially bimodal with peaks at 140–260 Ma and 1800–2000 Ma. Such a pattern is not recognized from the region of assumed origin before the opening of the South China Sea nor from the Indochina Peninsula. A similar bimodal pattern is observed on the Korean Peninsula, in coastal areas of the Shangdong Peninsula, and in Zhejiang Province in China. These areas are located at the marginal East China Sea. Hence, it is concluded that the Jurassic to Early Cretaceous sandstones of the Palawan microcontinent were parentally deposited on the eastern side of present-day Taiwan.

Key words: Palawan, monazite, age, sandstone, tectonics.

Introduction

The Palawan microcontinent is a small block consisting mainly of the north terrane of Palawan Island, Busuanga Island, the southwestern part of Mindoro Island, and the northwestern part of Panay Island (Fig. 1). The tectonic model of the microcontinent during the Tertiary has been well illustrated. The Palawan microcontinent 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 (Holloway, 1982). A magnetic anomalies in the South China Sea show that the spreading started from about 32 Ma and ended at 17 Ma (Taylor and Hayes, 1980). After that time period, the microcontinent began to collide with the Philippine Mobile Belt (Hamilton, 1979: Holloway, 1982: Yumul *et al*., 2003). The Palawan microcontinent consists of Upper Paleozoic to Mesozoic rocks (Hashimoto and Sato, 1973: Isozaki *et al*. 1987). The constituent rocks belong to oceanic plate stratigraphy or a subduction complex composed mainly of Permian to Upper Jurassic chert, Middle Jurassic to Cretaceous clastics, and limestone blocks of various ages (e.g. Isozaki *et al*. 1987: Zamoras & Matsuoka, 2001 &2004; Zamoras *et al*. 2008). Basaltic blocks and Cretaceous shallow marine sediments occur locally on the microcontinent (e.g. Zamoras and Matsuoka, 2001: Andal *et al*., 1968).

In this paper we study the provenances of the sandstones in the Palawan microcontinent to elucidate the location of the deposition or subduction at the time of the Jurassic to Early Cretaceous. The conventional approach to pro-

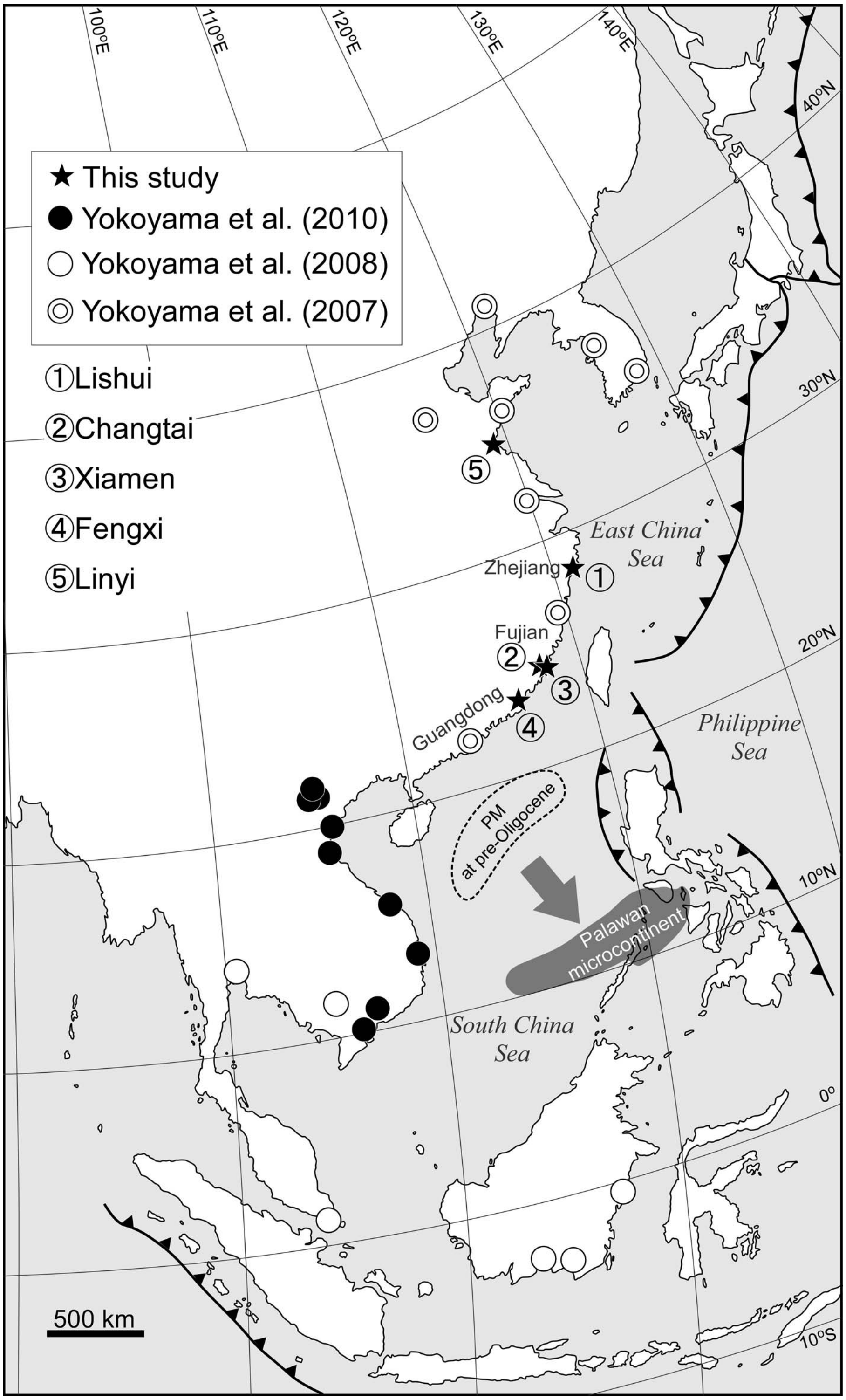


Fig. 1. Sampling localities of recent sands from Asia and the Palawan microcontinent. Reconstruction of the microcontinent before the opening of the South China Sea is of Zamoras and Matsuoka (2004).

venance studies of sandstones is based on determination of chemical compositions of detrital minerals in the sandstones and comparison with data from the Asian continent. The development of analytical techniques that allow age determinations to be made on individual mineral grains has provided a powerful tool in provenance studies. Many age dating 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. Wyck & Norman, 2004; Evans *et al*. 2001), and by monazite data via the electron probe micro-analyzer (EPMA) (e.g. Suzuki, Adachi & Tanaka, 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 Eastern Asia have already been reported (Fig. 1: Yokoyama *et al*., 2007, 2008, 2010), the monazite data will be a strong tool for comparison between the sandstones on the Palawan microcontinental block and the sands on the Asian coastal provinces.

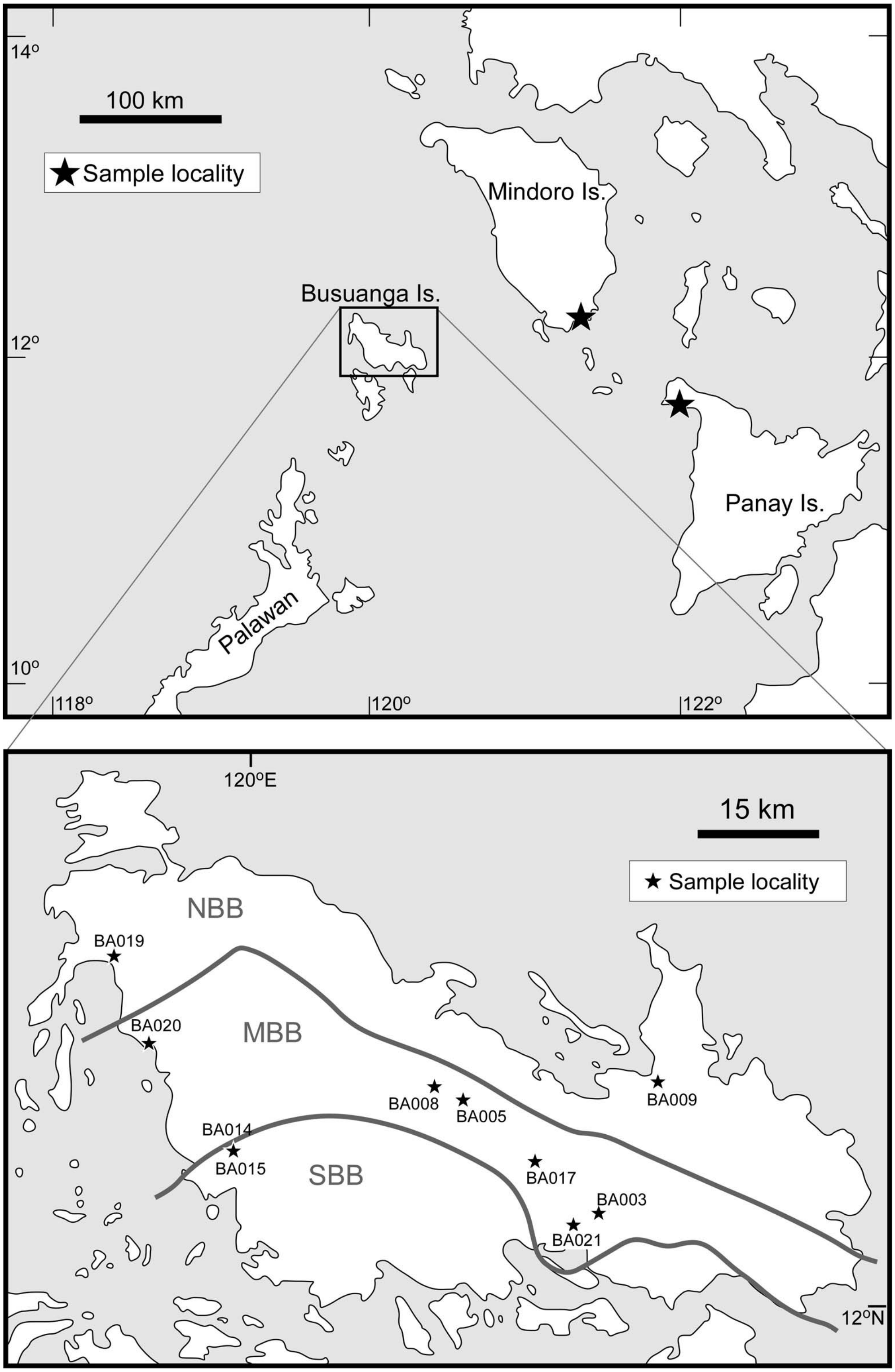
Geological setting

Most of the sandstone samples were collected from Busuanga Island, north of the Palawan block. Geological maps of the island were published by the Bureau of Mines and Geosciences (BMG) in 1984 and radiolarian ages of the chert-clastic sequences were later established by Zamoras and Matsuoka (2001 & 2004). According to BMG (1984), the island is composed of three formations: the King Ranch Formation, the Malajon Limestone, and the Liminangcong Formation. The King Ranch Formation is composed predominantly of tuffaceous shale and sandstone with intercalated tuff and minor thinly bedded chert, whereas the Liminangcong Formation is composed of bedded chert with interbedded indurated sandstone and shale. Zamoras and Matsuoka (2001) referred to the BMG (1984) geological map, but they used the name "Guinlo Formation" instead of the King Ranch Formation and the clastics in the Liminangcong Formation were treated as part of the "Guinlo Formation". Except for limestone blocks, Zamoras and Matsuoka (2001 & 2004) classified the rocks on the island into chert, siliceous mudstone, and terrigenous clastics and divided chert-clastic sequences in the Guinlo and Liminangcong formations into three belts on the basis of the radiolarian fossils in the terrigenous clastics: the Northern Busuanga (Middle Jurassic), Middle Busuanga (Late Jurassic), and Southern Busuanga (Early Cretaceous). Zamoras and Matsuoka (2001) described the sandstone in the Guinlo Formation occasionally as arkose sandstones and have not used the term "tuffaceous" for the clastics.

On the western part of Panay Island, a bedded chert and clastic sequence occurs. Although continuous succession from clastic rock to chert has not been confirmed, they are treated as a Jurassic subduction complex consisting of a chert-shale-clastic sequence corresponding to the Middle Busuanga belt (Zamoras *et al*. 2008). The sandstone is arenitic in composition. In the southwestern part of Mindoro Island, Jurassic shallow marine sediments occur. They are composed mainly of sandstone and shale with a thin layer of tuff. The sediments are rather rich in fossil remains. Late Middle to Early Late Jurassic ammonite, belemnite, and pelecypod were described (Andal *et al*. 1968). Many animal tracks are also observed in the Jurassic sediments. Some sandstone layers are frequently intercalated by black bituminous shale.

Sample Description

On Busuanga Island, about twenty sandstones were collected from the three belts of Zamoras and Matsuoka (2001 & 2004) as


14°
100 km
Sample locality
Mindoro Is.
Busuanga Is.
12°
Panay Is.
Palawan
10°
118°
120°
122°
120°E
15 km
Sample locality
NBB
BA019
MBB
BA020
BA008
BA005
BA009
BA014
BA015
SBB
BA017
BA003
BA021
12°N

shown in Fig. 2. Some samples were collected from the same route studied in detail by Zamoras and Matsuoka (2001). Sandstones were also collected from the shallow marine sediment in the southeastern part of Mindoro Island and from a clastic sequence in the western part of Panay Island.

On Busuanga Island, there are two types of sandstones which correspond to those from the King Ranch Formation and the Liminangcong Formation described in the BMG (1984). The sandstones from the King Ranch Formation are poor in quartz and feldspar grains (Fig. 3). Clay minerals are abundant and loosely packed. And, just as described by the BMG (1984), the clay minerals are identified as being "tuffaceous". On the other hand, sandstones from the Liminangcong Formation are indurated samples. They are also poor in quartz and feldspar fragments (Fig. 3). The differences between them are simply due to later stage metamorphism as described later in this paper. Most of the collected samples from Busuanga Island are tuffaceous, which is different from the quartzose or arkose sandstones on Mindoro and Panay islands (Fig. 3). One sample, BA017, was collected from an outcrop along a newly reconstructed road. The outcrop belongs to the Middle Busuanga Belt and consists of sandstone and shale. The shale is bituminous and locally contains a thin patch of coal (Fig. 3). Sand pipe, a possible trace fossil, is common in the sandstones from both sides of the bituminous shale. Although we did not observe a clear transition from sandstone to chert, BMG (1984) described the intercalation of tuffaceous sandstone and chert, and Zamoras and Matsuoka (2001) treated the sandstone as a part of the chert-siliceous shale-terrigenous clastic sequence of the subduction complex. Both the sandstone samples from the Mindoro and Panay islands are indurated calcareous quartzose sandstone and arkose sandstone, respectively (Fig. 3).

In addition to the sandstone samples from the Palawan microcontinent, a few river sands, BA019 and BA020, were collected from the western part of Busuanga Island (Fig. 2). Additionally, five sand samples were newly collected from the southern coastal provinces of the Asian continent (Fig. 1). Characteristics of the major river sands from the Asian continent (Fig. 1) have been reported by Yokoyama et al. (2007, 2008, & 2010). The present sand samples will also provide indicators of probable provenance areas on the assumption that the Palawan microcontinent was separated from the Asian continent.

Analytical Procedures

Procedures for the separation of heavy minerals and their subsequent identification are the same as have been described by Yokoyama *et al*. (1990). Carbonate and micaceous minerals were not subjected to examination, and magnetic fractions were removed prior to the separation of the heavy minerals. Modal proportions of representative heavy minerals are shown in Table 1. The light minerals are less source-diagnostic and therefore are not a major focus in this provenance study.

Among the heavy minerals, monazite is the most important for elucidating the provenance. The theoretical basis for monazite age calculations is essentially the same as that developed by Suzuki *et al*. (1991). Monazites were analyzed by the EPMA fitted with a Wavelength Dispersive Spectrometer (WDS) JXA-8800 situated in the National Museum of Natureand Science. Analytical conditions used here have been described by Santosh *et al*.

Fig. 2. Sampling localities of sandstones on Busuanga, Mindoro, and Panay islands. Three belts, NBB, MBB, and SBB, are abbreviations for the Northern Busuanga, Middle Busuanga, and Southern Busuanga belts of Zamoras and Matsuoka (2004).

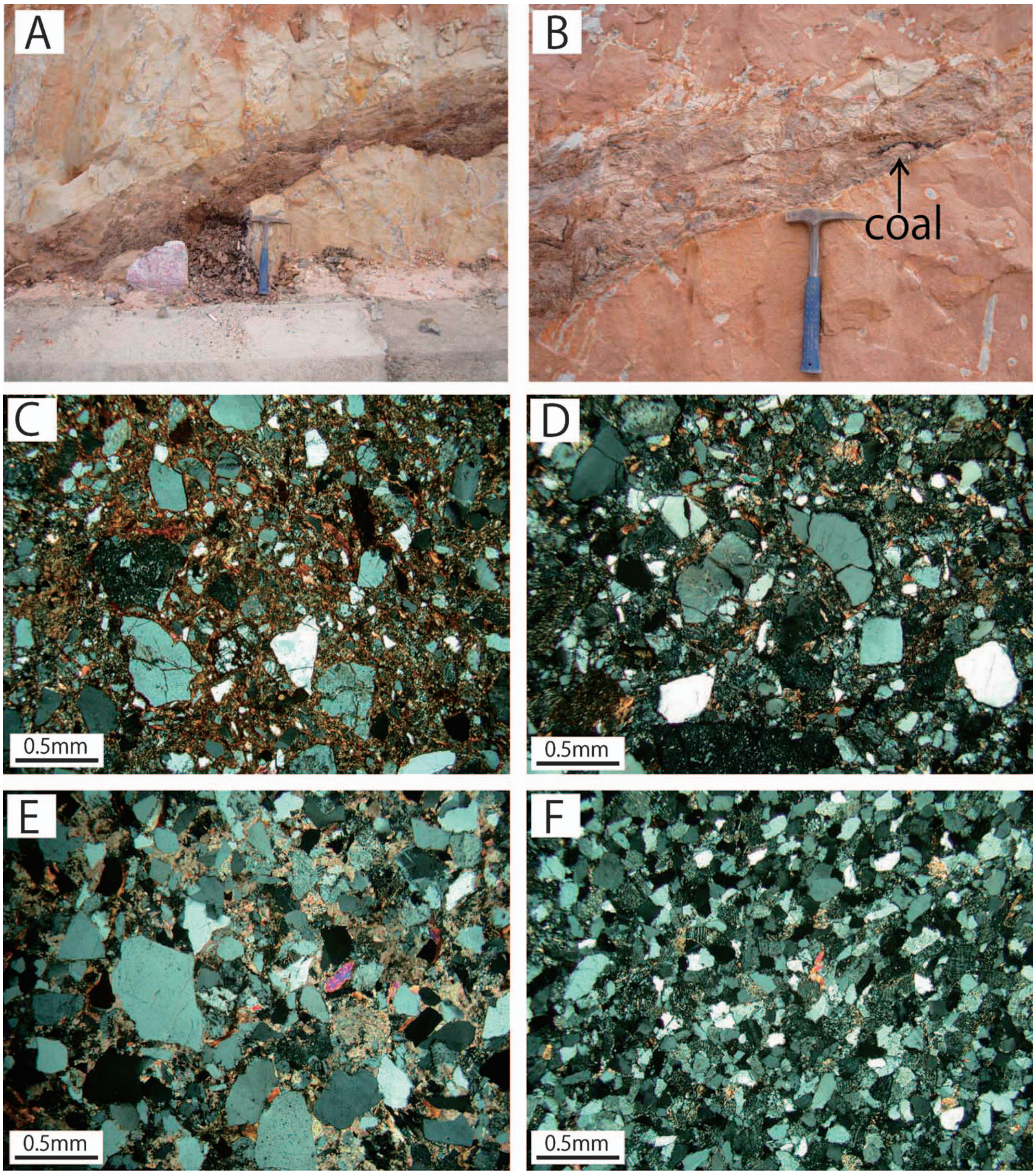


Fig. 3. A & B: outcrop showing a bituminous shale layer, dark part, with coal patch. Sand pipes develop in the sandstones. Sampling locality BA017. C∼F: photomicrograph of sandstone (crossed polars). C: tuffaceous sandstone, BA005. D: well-solidified sandstone (possibly tuffaceous) BA002. E: calcareous quartzose sandstone from the Mindoro Island. F: arkose sandstone from the Panay Island.

(2003). Age calibrations were carefully performed by comparing data obtained from EPMA dating with those acquired via 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 both techniques were found to have good consistency. Monazites with ages of 3020 Ma and 64 Ma that were obtained by SHRIMP zircon and K-Ar mica methods, respectively, have been used as internal standards for age calibrations. The standard deviation of

Table 1. Heavy mineral species in the sandstones from Busuanga, Mindoro, and Panay islands. Numbers show grains counted properly from the heavy fractions under energy dispersive spectrum. garnet: Fe-rich garnet. gr-and: grossular-andradite series garnet. TiO_2: TiO_2 polymorphs. epidote: epidote group minerals. Sand*: sample BA019 & $BA0_20$

formation*1	KR	KR	LM	LM	LM	LM	LM	LM	KR	KR	KR	KR	KR	KR	Mindoro Is.	Panay Is.
belt*2	NBB	NBB	NBB	NBB	NBB	MBB	MBB	MBB	MBB	MBB	MBB	MBB	SBB	SBB		
sample No.	BA007	BA009	BA010	BA011	BA012	BA001	BA002	BA003	BA004	BA005	BA008	BA017	BA014	BA015		
garnet	8		19		14	91	51	18		57		1		2	65	14
gr-and				1		2										
epidote	14	94			74	24		17								6
TiO_2	13	129	29	4	20	8	53	33	11	66	49	52	60	58	56	19
zircon	47	68	18	10	33	53	70	19	34	79	92	109	95	42	153	81
titanite			40		47	7										25
apatite			1		2		7								27	13
tourmaline	1	2	1			1	6	1		3		1		5	5	6
allanite			1		1			1						3		1
ilmenite	106					3										7
spinel		2	2				3			2	1		40	35		3
monazite	20	1	pre*3		pre	6		3		2	2	3	5	2	29	pre
xenotime							1					1	2	1		
thorite	1	1								1						
total	210	203	205	14	192	195	191	92	45	210	144	167	202	148	175	335

*1: formation of KGM(1984) KR: King Ranch, LM: Liminangcong

*2: belts of Zamorasu and Matsuoka (2001),NBB: North Busuanga Belt, MBB: Middle Busuanga Belt, SBB: South Busuanga Belt

*3: pre:present

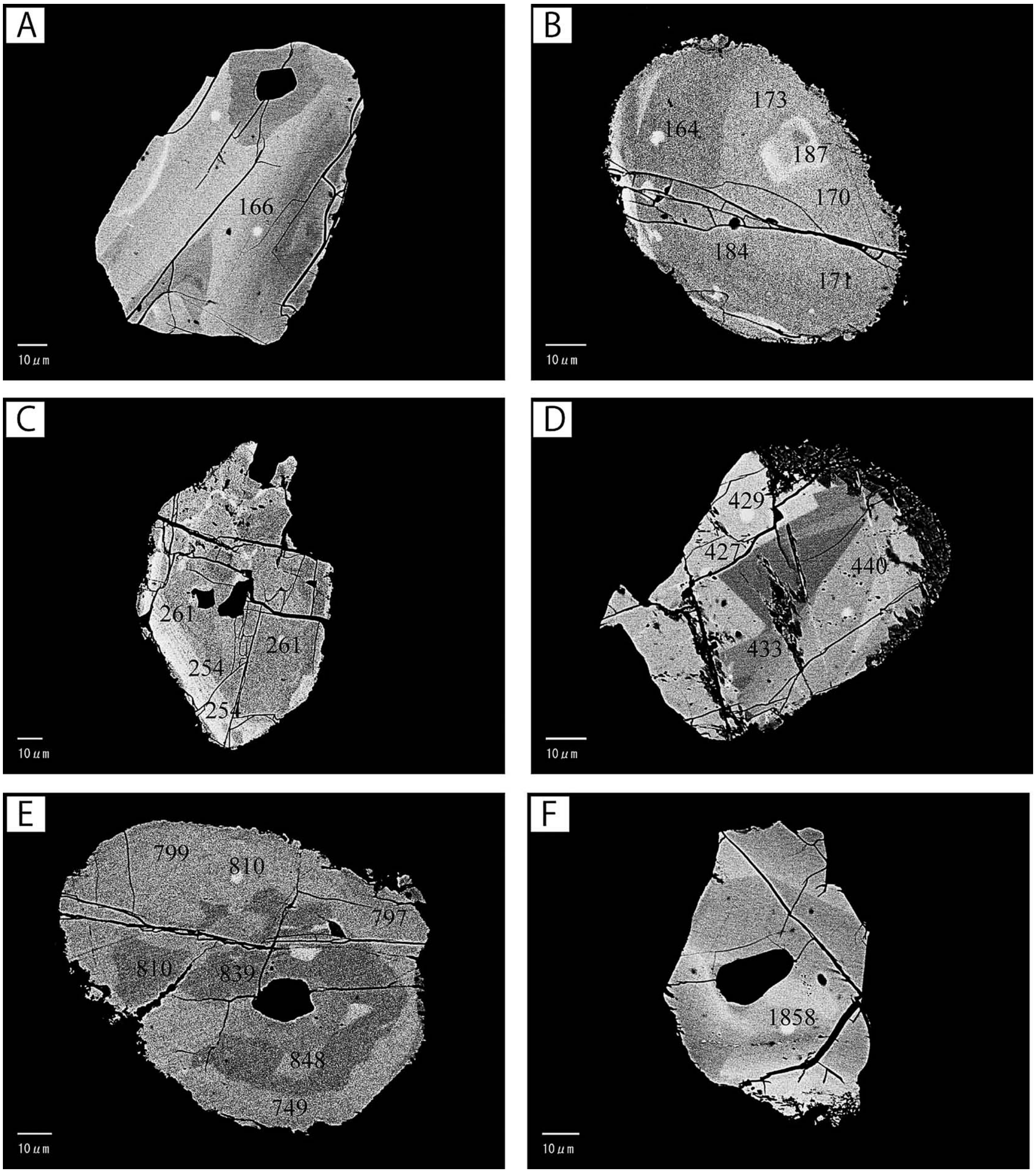


Fig. 4. Back-scattered images of detrital monazites with various ages. A & B: monazites with ages less than 200 Ma. C: monazite with age around 260 Ma. D & E: rare monazites with 430 Ma and 800 Ma, respectively. F: monazite with 1860 Ma. The number in each grain shows monazite age (Ma).

the age obtained depends mostly on the PbO content of the monazite. The errors for the age are within a few percent for most of the analyzed monazites that were rich in ThO_2.

Among the other heavy minerals, we analyzed chemical compositions of spinel and garnet by EPMA.

Heavy Minerals

Although many sandstone samples are tuffaceous and poor in heavy minerals, fourteen mineral species were observed in the heavy fractions and the abundance of each of the mineral species has been determined (Table 1). A restricted number of species is due to the common dissolution of some detrital mineral species in the sandstones (e.g. Pettijohn, 1941; Morton, 1984 & 1991). Among the common heavy minerals, zircon, monazite, spinel, tourmaline, TiO_2 polymorphs, and garnet are considered to be ultrastable minerals. Apatite and xenotime are rare in the sediments and are also treated as detrital minerals.

As a result of the dissolution of unstable heavy minerals, zircon and TiO_2 polymorphs are predominant in the heavy fractions of most of the sandstones (Table 1). Garnet and spinel are occasionally abundant. Apatite, tourmaline, and monazite are sporadic and mostly found in small quantities. Both epidote and titanite usually occur in well solidified sandstones belonging to those from the Liminangcong Formation of the BMG (1984). In addition to grossular-andradite series garnet and allanite, these minerals have been totally dissolved in Jurassic to Cretaceous sandstones (Yokoyama and Goto, 2000: Yokoyama and Saito, 2001). The presence of such less-resistant minerals shows that the sandstones suffered from a weak metamorphism.

Monazite is mostly small or scarce in quantity and less than a few percent of the heavy fraction of the sandstones (Table 1). Monazite grains are mostly rounded or sub-rounded suggesting a detrital origin (Fig. 4). Angular or decomposed monazite occurs in the well solidified sandstones from the Liminangcong Formation. Such monazite texture was reported from weakly metamorphosed sandstones on the Japanese Islands and Taiwan (Yokoyama & Goto, 2000; Yokoyama *et al*., 2007). The monazite is clearly a secondary post depositional mineral, supporting the idea that the sandstones in the Liminangcong Formation were more or less metamorphosed. Occasionally, rounded monazite is surrounded by angular monazite aggregate. In the sandstone BA007 and sandstone from Mindoro Island monazite is common; consisting of about 10% of the heavy minerals. Monazite from sandstone BA007 occurs as an aggregate, showing decomposition by a later stage metamorphic event. On the other hand, the monazite from the Mindoro Island sandstone is usually rounded detrital grain.

Heavy fractions of the river sands from Busuanga Island and the Asian continent were collected by panning. Monazite is mostly an angular and fine-grained aggregate in the samples from Busuanga Island. However, a number of mostly rounded or sub-rounded grains of monazite have been observed in the sands recently collected from the Asian continent.

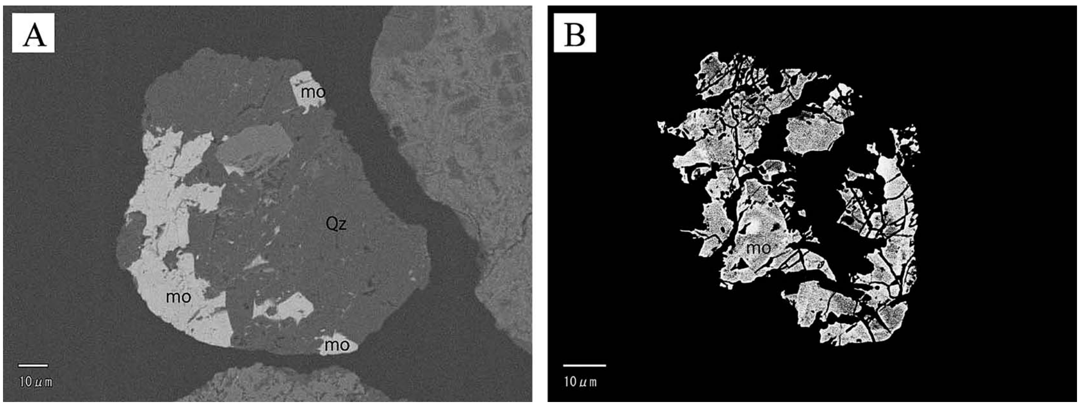


Fig. 5. Back-scattered images of secondary monazites with ages around 100 Ma. A & B: decomposed monazite usually fine-grained and forming aggregate.

Table 2. Age data of monazites in the sandstones and sands from the Palawan microcontinent and coastal regions of China (Figs. 1 & 2).

	Busuanga							
Age (Ma)	BA03	BA05	BA08	BA09	BA14	BA15	BA17	sands*
0	0	0	0	0	0	0	0	0
0.25	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0
0.75	0	0	0	0	0	0	0	2
1	0	0	0	0	0	0	0	8
1.25	0	0	0	0	1	0	2	0
1.5	1	9	4	4	9	3	46	6
1.75	2	7	4	7	10	7	47	4
2	0	0	0	1	1	2	2	2
2.25	0	0	1	2	6	1	2	3
2.5	0	0	0	0	1	0	3	3
2.75	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
3.25	0	0	0	0	0	0	0	0
3.5	0	0	0	0	0	0	0	0
3.75	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
4.25	0	0	0	0	0	0	1	0
4.5	0	0	0	0	0	0	0	0
4.75	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
5.25	0	0	0	0	0	0	0	0
5.5	0	0	0	0	0	0	0	0
5.75	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
6.25	0	0	0	0	0	0	0	0
6.5	0	0	0	0	0	0	0	0
6.75	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
7.25	0	0	0	0	0	0	0	0
7.5	0	0	1	0	0	0	0	0
7.75	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
8.25	0	0	0	0	0	0	0	0
8.5	0	0	0	0	0	0	0	0
8.75	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
9.25	0	0	0	0	0	0	0	0
9.5	0	0	0	0	0	0	0	0
9.75	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
10.25	0	0	0	0	0	0	0	0
10.5	0	0	0	0	0	0	0	0
10.75	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0
11.25	0	0	0	0	0	0	0	0
11.5	0	0	0	0	0	0	0	0
11.75	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0
12.25	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0
12.75	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0
13.25	0	0	0	0	0	0	0	0
13.5	0	0	0	0	0	0	0	0

Age (Ma)	Mindoro	Panay
0	0	0
0.25	0	0
0.5	0	0
0.75	0	0
1	0	0
1.25	0	0
1.5	18	0
1.75	46	0
2	68	2
2.25	89	1
2.5	35	0
2.75	0	0
3	1	0
3.25	0	0
3.5	0	0
3.75	0	0
4	0	0
4.25	0	0
4.5	0	0
4.75	0	0
5	0	0
5.25	0	0
5.5	0	0
5.75	0	0
6	0	0
6.25	0	0
6.5	0	0
6.75	0	0
7	0	0
7.25	0	0
7.5	0	0
7.75	0	0
8	0	0
8.25	0	0
8.5	0	0
8.75	0	0
9	0	0
9.25	0	0
9.5	0	0
9.75	0	0
10	0	0
10.25	0	0
10.5	0	0
10.75	0	0
11	0	0
11.25	0	0
11.5	0	0
11.75	0	0
12	0	0
12.25	0	0
12.5	0	0
12.75	0	0
13	0	0
13.25	0	0
13.5	0	0

	coastal area of Asian continent				
Age(Ma)	Ou R.	Jiulong R.	Gulong Is.	Han R.	Yi R.
0	0	0	0	0	0
0.25	0	0	0	0	0
0.5	0	0	0	0	0
0.75	4	6	6	3	1
1	26	45	43	3	0
1.25	13	46	12	40	0
1.5	3	22	2	52	0
1.75	3	8	0	15	0
2	21	17	0	19	0
2.25	177	26	1	48	0
2.5	64	4	0	10	0
2.75	0	0	0	0	0
3	0	0	0	0	0
3.25	0	0	0	0	0
3.5	0	0	0	0	0
3.75	1	0	0	0	0
4	2	8	0	5	0
4.25	1	9	1	15	0
4.5	0	4	0	5	0
4.75	0	0	0	0	0
5	0	0	0	0	0
5.25	0	0	0	0	0
5.5	0	0	0	0	0
5.75	0	0	0	0	0
6	0	0	0	0	1
6.25	0	0	0	0	0
6.5	0	0	0	0	0
6.75	0	0	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	0	0
8	0	0	0	0	0
8.25	0	0	0	0	0
8.5	0	0	0	0	0
8.75	0	0	0	0	0
9	0	0	0	0	0
9.25	0	0	0	0	0
9.5	0	0	0	1	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	0	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	0	0	0	0
13.25	0	0	0	0	0
13.5	0	0	0	0	0

Table 2. (continued)

	Busuanga												coastal area of Asian continent				
Age (Ma)	BA03	BA05	BA08	BA09	BA14	BA15	BA17	sands*	Age (Ma)	Mindoro	Panay	Age(Ma)	Ou R.	Jiulong R.	Gulong Is.	Han R.	Yi R.
13.75	0	0	0	0	0	0	0	0	13.75	0	0	13.75	0	0	0	0	0
14	0	0	0	0	0	0	0	0	14	0	0	14	0	0	0	0	0
14.25	0	0	0	0	0	0	0	0	14.25	0	0	14.25	0	0	0	0	0
14.5	0	0	0	0	0	0	0	0	14.5	0	0	14.5	0	0	0	0	0
14.75	0	0	0	0	0	0	0	0	14.75	0	0	14.75	0	0	0	0	0
15	0	0	0	0	0	0	0	0	15	0	0	15	0	0	0	0	0
15.25	0	0	0	0	0	0	0	0	15.25	0	0	15.25	0	0	0	0	0
15.5	0	0	0	0	0	0	0	0	15.5	0	0	15.5	0	0	0	0	0
15.75	0	0	0	0	0	0	0	0	15.75	0	0	15.75	0	0	0	0	0
16	0	0	0	0	0	0	0	0	16	0	0	16	0	0	0	0	0
16.25	0	0	0	0	0	0	0	0	16.25	0	0	16.25	0	0	0	0	0
16.5	0	0	0	0	0	0	0	0	16.5	0	0	16.5	0	0	0	0	0
16.75	0	0	0	0	0	0	0	0	16.75	0	0	16.75	1	0	0	0	0
17	0	0	0	0	0	0	0	0	17	0	0	17	0	0	0	0	0
17.25	0	0	0	0	0	0	1	0	17.25	1	0	17.25	1	0	0	0	0
17.5	0	0	0	0	0	0	0	0	17.5	0	0	17.5	0	0	0	0	0
17.75	0	0	0	0	0	1	0	0	17.75	1	0	17.75	0	0	0	0	0
18	0	0	0	1	0	0	1	0	18	13	0	18	3	0	0	0	0
18.25	0	1	1	1	5	1	1	0	18.25	31	0	18.25	7	2	0	0	3
18.5	0	0	2	1	2	1	9	0	18.5	66	0	18.5	7	0	0	0	1
18.75	0	2	2	0	2	1	4	2	18.75	71	3	18.75	4	0	0	0	1
19	0	0	0	0	0	1	0	0	19	58	1	19	2	2	0	2	0
19.25	0	0	0	0	0	0	0	0	19.25	14	1	19.25	1	0	0	0	0
19.5	0	0	0	0	0	0	0	0	19.5	1	0	19.5	0	0	0	0	1
19.75	0	0	0	0	0	0	0	0	19.75	0	0	19.75	0	0	0	0	0
20	0	0	0	0	0	0	0	0	20	0	0	20	0	0	0	0	0
20.25	0	0	0	0	0	0	0	0	20.25	0	0	20.25	0	0	0	0	0
20.5	0	0	0	0	0	0	0	0	20.5	0	0	20.5	0	0	0	0	0
20.75	0	0	0	0	0	0	0	0	20.75	0	0	20.75	0	0	0	0	0
21	0	0	0	0	0	0	0	0	21	0	0	21	0	0	0	0	0
21.25	0	0	0	0	0	0	0	0	21.25	0	0	21.25	0	0	0	0	0
21.5	0	0	0	0	0	0	0	0	21.5	0	0	21.5	0	0	0	0	0
21.75	0	0	0	0	0	0	0	0	21.75	0	0	21.75	0	0	0	0	0
22	0	0	0	0	0	0	0	0	22	0	0	22	0	0	0	0	0
22.25	0	0	0	0	0	0	0	0	22.25	0	0	22.25	0	0	0	0	0
22.5	0	0	0	0	0	0	0	0	22.5	0	0	22.5	0	0	0	0	0
22.75	0	0	0	0	0	0	0	0	22.75	0	0	22.75	0	0	0	0	0
23	0	0	0	0	0	0	0	0	23	0	0	23	0	0	0	0	0
23.25	0	0	0	0	0	0	0	0	23.25	0	0	23.25	0	0	0	0	0
23.5	0	0	0	0	0	0	0	0	23.5	0	0	23.5	0	0	0	0	0
23.75	0	0	0	0	0	0	0	0	23.75	0	0	23.75	0	0	0	0	0
24	0	0	0	0	0	0	0	0	24	0	0	24	0	0	0	0	0
24.25	0	0	0	0	0	0	0	0	24.25	0	0	24.25	0	0	0	0	1
24.5	0	0	0	0	0	0	0	0	24.5	0	0	24.5	0	0	0	0	5
24.75	0	0	0	0	0	0	0	0	24.75	0	0	24.75	0	0	0	0	11
25	0	0	0	0	0	0	0	0	25	0	0	25	0	0	0	0	10
25.25	0	0	0	0	0	0	0	0	25.25	0	0	25.25	0	0	0	0	10
25.5	0	0	0	0	0	0	0	0	25.5	0	0	25.5	0	0	0	0	5
25.75	0	0	0	0	0	0	0	0	25.75	0	0	25.75	0	0	0	0	0
26	0	0	0	0	0	0	0	0	26	0	0	26	0	0	0	0	0
Total	3	19	15	17	37	18	119	30		513	8		341	199	65	218	50

Age of Monazite

Monazite is a rare earth elements (REEs)-bearing phosphate mineral occurring as an accessory mineral in granitic and high-grade metamorphic rocks and in sands derived from them. 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 usually less than a few percent in old monazites ($>$ca. 300 Ma) or less than 25 Ma in younger monazites ($<$ca. 300 Ma). One representative age has been selected from each grain. A list of the age data is shown in Table 2. A total of 1652 grains have been analyzed in this study: 258 grains from Busuanga Island, 513 grains from Mindoro Island and 873 grains from the Asian continent. Only 8 monazite grains were analyzed in the sandstone from Panay Island, probably due to the later stage metamorphic effect. Back-scattered electron images of representative detrital and secondary grains are shown in Fig. 4 and 5, respectively. Monazite ages from the Palawan micro-continent and Asian continent are presented as probability diagrams in Fig. 6 and 7, respectively. Probability distributions for monazite ages were calculated with a multi-peak Gaussian fitting method (e.g. Williams, 1998). As monazite is rare or scarce in the sandstone samples from Busuanga Island, all the data from the sandstone samples obtained from the island are presented in one of the diagrams in Fig. 6. Many monazite grains in the sand samples from the islands are fine and angular, which is different from the rounded grains. They are presented in the other diagram in Fig. 6.

Ages of rounded or sub-rounded monazite grains from Busuanga Island range from ca. 140 Ma to 2200 Ma, apparently showing bimodal distribution with strong clusters at 150–270 Ma and 1800–1950 Ma, while monazites with ages ranging from 300 Ma to 1800 Ma are scarce (Fig. 6). The major peak is at 176$\pm$19 Ma. Small peaks are located at 240 $\pm$24 Ma and 1860$\pm$34 Ma. Those from Mindoro and Panay islands also exhibit a bimodal distribution similar to those from Busuanga Island (Fig. 6). Age data from Mindoro Island have major peaks at 230$\pm$27 Ma and 1880$\pm$43 Ma and a minor peak at 177 $\pm$18 Ma. Considering the standard deviation of each peak position, these peak positions are similar to those from Busuanga Island. Although a notably different age distribution pattern is not observed among the sandstones from Busuanga, Mindoro, and Panay islands, monazites with 430 Ma and 770 Ma are observed in the sandstones from Busuanga Island. Such an age is totally absent in the monazites from Mindoro Island.

In the well-consolidated sandstones from Liminangcong Formation and sands from the western part of the island, monazites are mostly angular in shape. Such monazites show an age peak at around 100 Ma (Fig. 6).

Additional data collected from the coastal zone of the Asian continent have sands with monazite ages that are shown in Fig. 7. The sand samples have distinct age distribution characteristics, reflecting the different rocks in their drainage basins. In the Lishui samples, monazite is bimodal with peaks at 100 Ma and 1900 Ma. Whereas the Changtai and Fengxi have different distribution patterns: peaks at 40 Ma and 230 Ma. The sand from the Linyi also has a different pattern that shows a strong peak at 2500 Ma. The oldest monazites are supplied from an Archean terrane-the Tishan Mountains-in the drainage basin.

In southeast Asia (Sundaland), age patterns in the sands are represented by a strong peak at 250 Ma and no clear peak at 1900 Ma (Yokoyama *et al.*, 2010). In the Yangtze River, most of the sands are characterized by a strong peak at 400 Ma and small peak at 700 Ma. Bimodal distribution with peaks at 250 and 1900 Ma is observed widely on the Korean Peninsula.

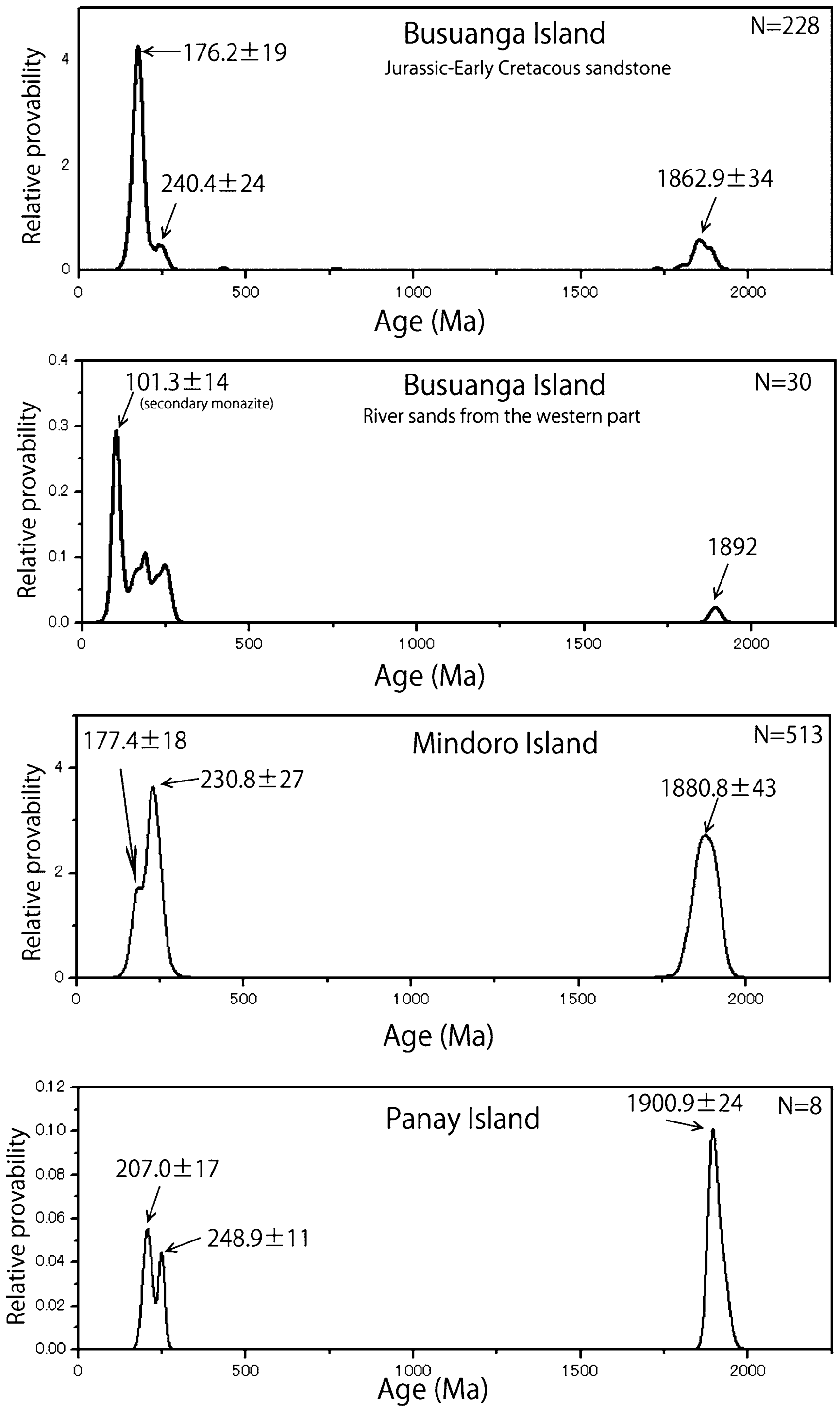
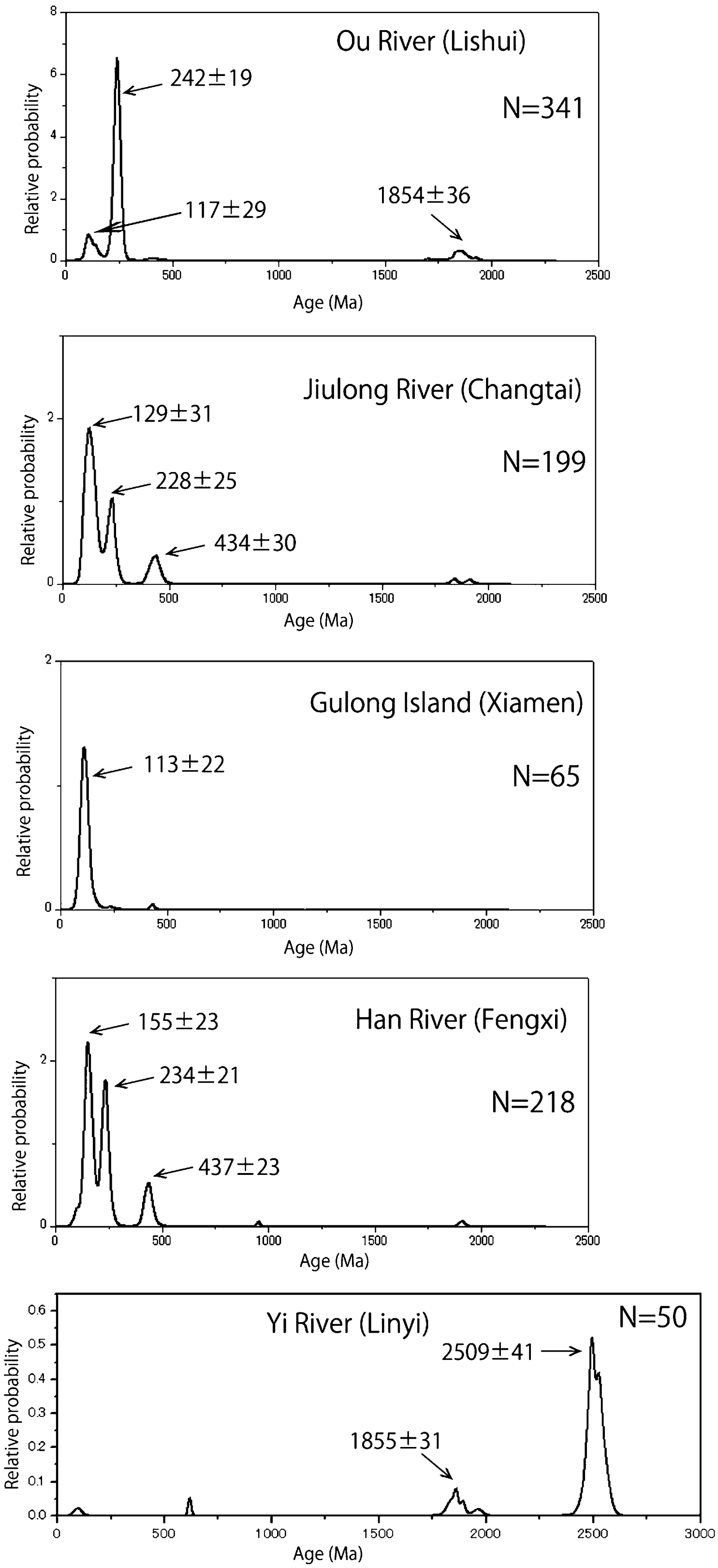


Fig. 6. Probability distribution diagrams of monazite ages in the sandstones and sands from Busuanga, Mindoro, and Panay islands. Numerical value (n) denotes the number of analyzed monazite grains.


Ou River (Lishui)
N=341
242±19
117±29
1854±36
Relative probability
Age (Ma)
Jiulong River (Changtai)
N=199
129±31
228±25
434±30
Relative probability
Age (Ma)
Gulong Island (Xiamen)
N=65
113±22
Relative probability
Age (Ma)
Han River (Fengxi)
N=218
155±23
234±21
437±23
Relative probability
Age (Ma)
Yi River (Linyi)
N=50
2509±41
1855±31
Relative probability
Age (Ma)

Chemical compositions of spinel and garnet

Chemical compositions of spinel and garnet are source diagnostic and well summarized by many authors (e.g. Kamenetsky *et al*., 2001; Yokoyama et al., 1990). Spinel is derived from various types of basalt, gabbro, and peridotite. It is abundant in the sandstones from the South Busuanga Belt, whereas it is small in quantity in the other sandstones. Spinel from the South Busuanga Belt commonly contains glass inclusions and rarely olivine (Fig. 8). Garnet is sporadically abundant. There is no correlation between the modal proportion of garnet and the classified belts on Busuanga Island.

The chemical composition of spinel is plotted in the TiO_2–MgO diagram by Kamenetsky *et al*. (2001). Spinels from the Southern Busuanga Belt are characterized by high TiO_2 content and are mostly plotted in an area of ocean-island basalt (Fig. 9). On the other hand, spinels in the Middle and Northern belts are low in TiO_2 showing that they are mostly derived from peridotite and are rarely from an ocean-island basalt region. Spinels from the Mindoro and Panay islands are also TiO_2-poor, and are mainly plotted in a peridotite region.

Garnet is plotted in Ca–Mg–Fe and Ca–Mn–Fe diagrams (Fig. 10), and is usually derived from metamorphic rocks. Generally speaking, Mg content in garnet is related to the metamor-

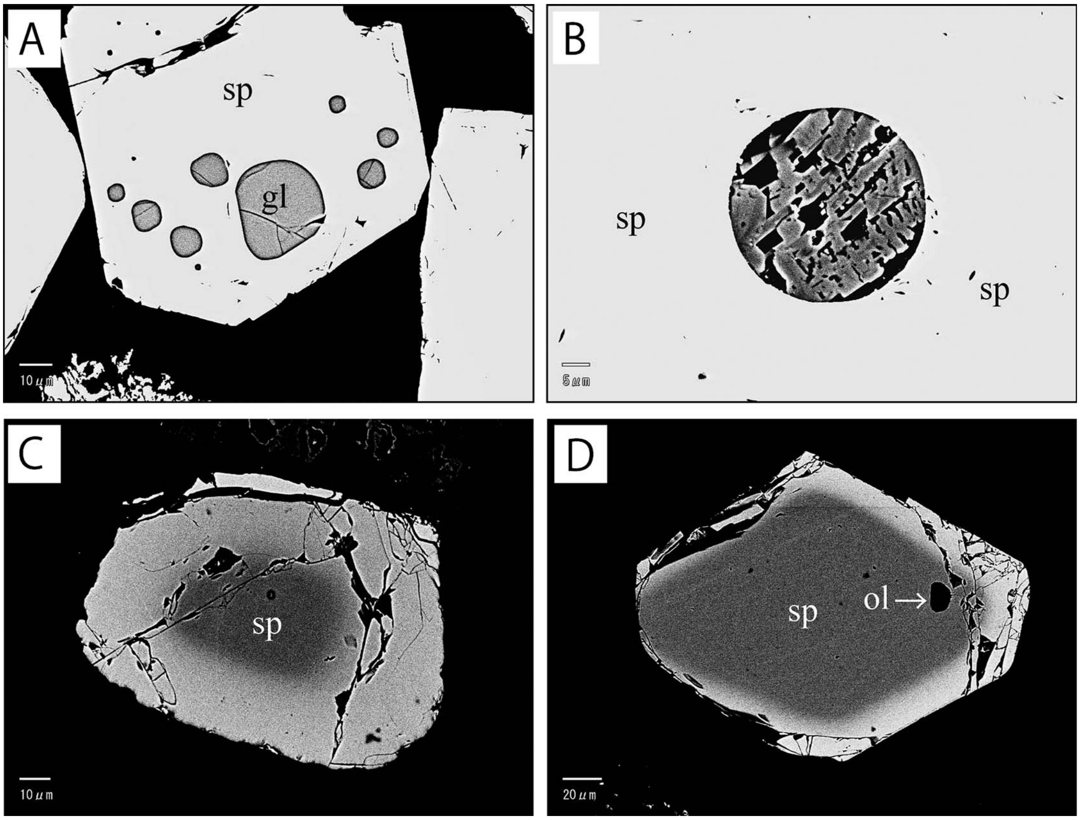


Fig. 8. Back-scattered images of detrital spinels in BA014 & BA015. A: spinel (sp) with glass inclusions (gl). B: devitrified glass inclusion in spinel. C: spinel with zoning texture. D: olivine inclusion (ol) in zoned spinel.

Fig. 7. Probability distribution diagrams of monazite ages in the sands collected along the East Asian continental margin. Numerical value (n) denotes the number of analyzed monazite grains.

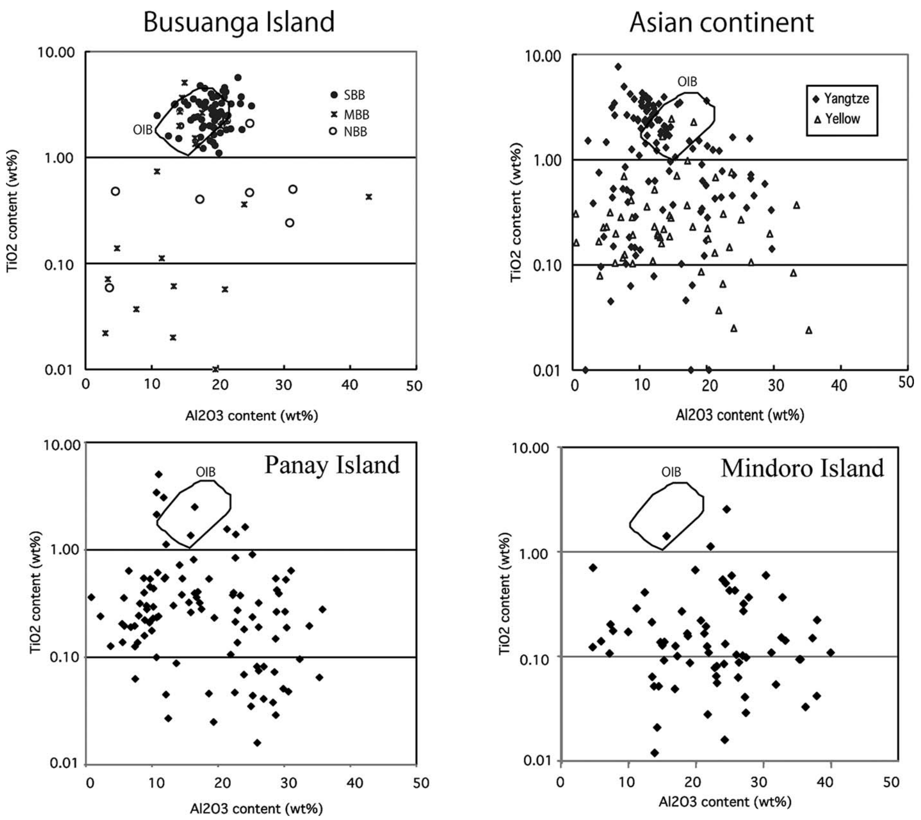


Fig. 9. Al_2O_3 vs TiO_2 compositional relationships in detrital spinels from the Palawan microcontinent and the Asian continent. Compositional variation of spinel from oceanic island basalt is enclosed by a solid line (Kamenetsky *et al.*, 2001). TiO content of spinel from peridotite is usually less than 1.0 wt%.

phic grade: Mg-rich indicates a high grade of metamorphism while Mg-poor indicates a lower grade. Ca-rich garnet, more than 10% in grossuilar content, is derived from metamorphic rock with a basaltic composition, whereas Ca-poor one is of a pelitic composition. Garnets from the Busuanga and Mindoro islands are relatively poor in Mg content, with less than a 25% pyrope component. There is no clear difference in garnet composition between those from Busuanga Island and Mindoro Island. It shows that high-grade metamorphic terrane was absent in their provenances. It is noteworthy that the Ca-rich garnets from both islands are also preserved. Generally, Ca-rich garnet has been totally dissolved in sandstones from the Jurassic subduction complex of the Japanese Islands (Yokoyama and Saito, 2001). On the other hand, garnets from Panay Island are Mg-rich and depleted in CaO content which is common in the sandstones from the subduction complex of the Japanese Islands. This phenomenon is explained by selective dissolution after subduction rather than an absence of Ca-rich garnet in the drainage basin (Yokoyama and Saito, 2001).

Discussion

Provenance of detrital monazite

Age of detrital monazite has produced significant information on the provenance of the sandstones from the Palawan microcontinent. The microcontinent is considered to have been located at the southwestern part of Taiwan and separated from the Asian continent during the

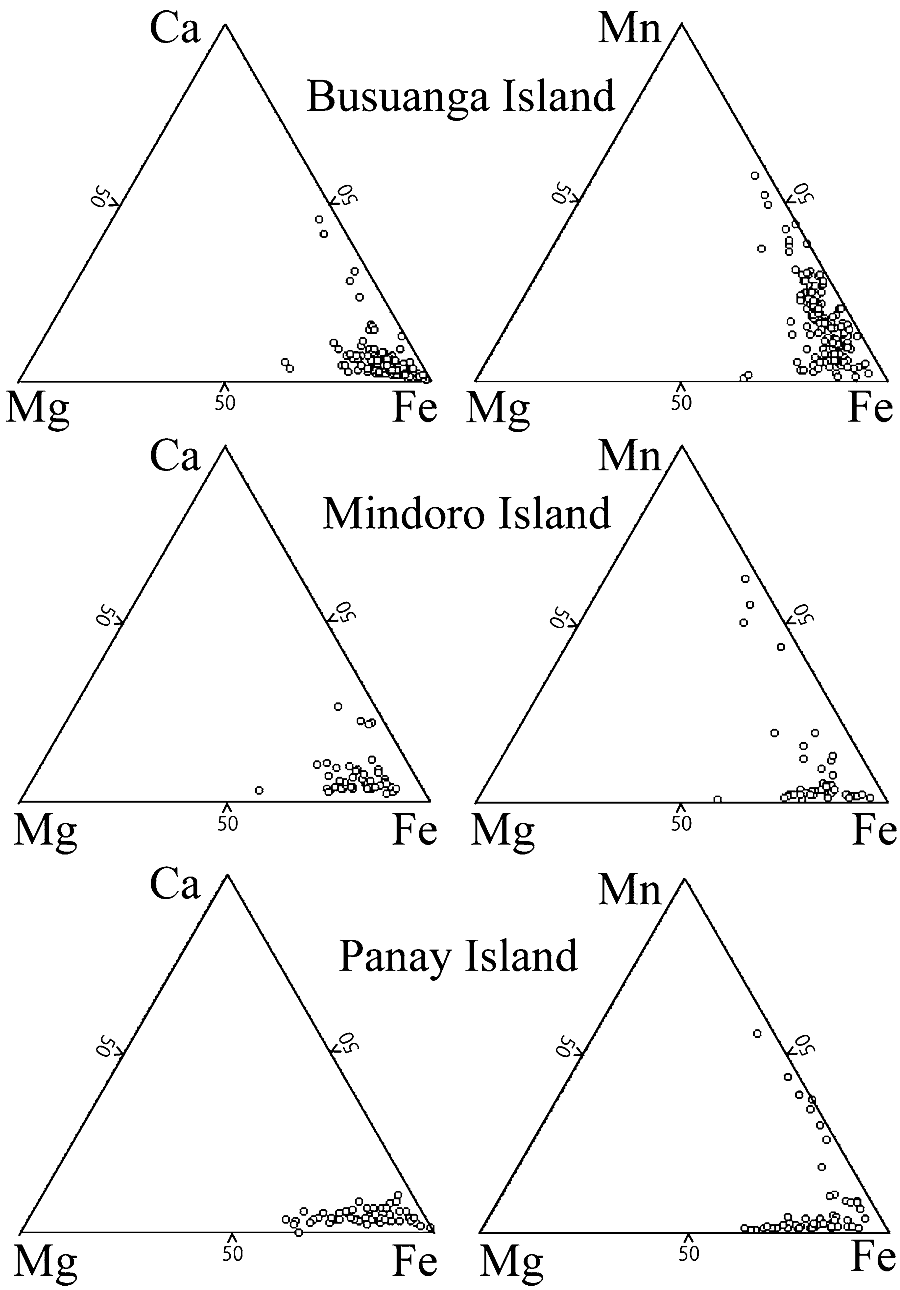


Fig. 10. Compositional variations of detrital garnets from Busuanga, Mindoro, and Panay islands. Each datum is plotted in Ca–Mg–Fe and Mn–Mg–Fe diagrams.

opening of the South China Sea (e.g. Holloway, 1982: Zamoras and Matsuoka, 2004). Ages of monazites in the sands from the coastal zone of the Asian continent have been reported (Fig. 1: Yokoyama *et al.*, 2007, 2008, 2010). In this study, we have determined the ages of detrital monazites in the sandstones from the Palawan microcontinent. Hence, comparison of the Palawan data with equivalent data in sands from the Asian continent should deduce the provenance of the detrital monazite and the original depositional site for the Jurassic to

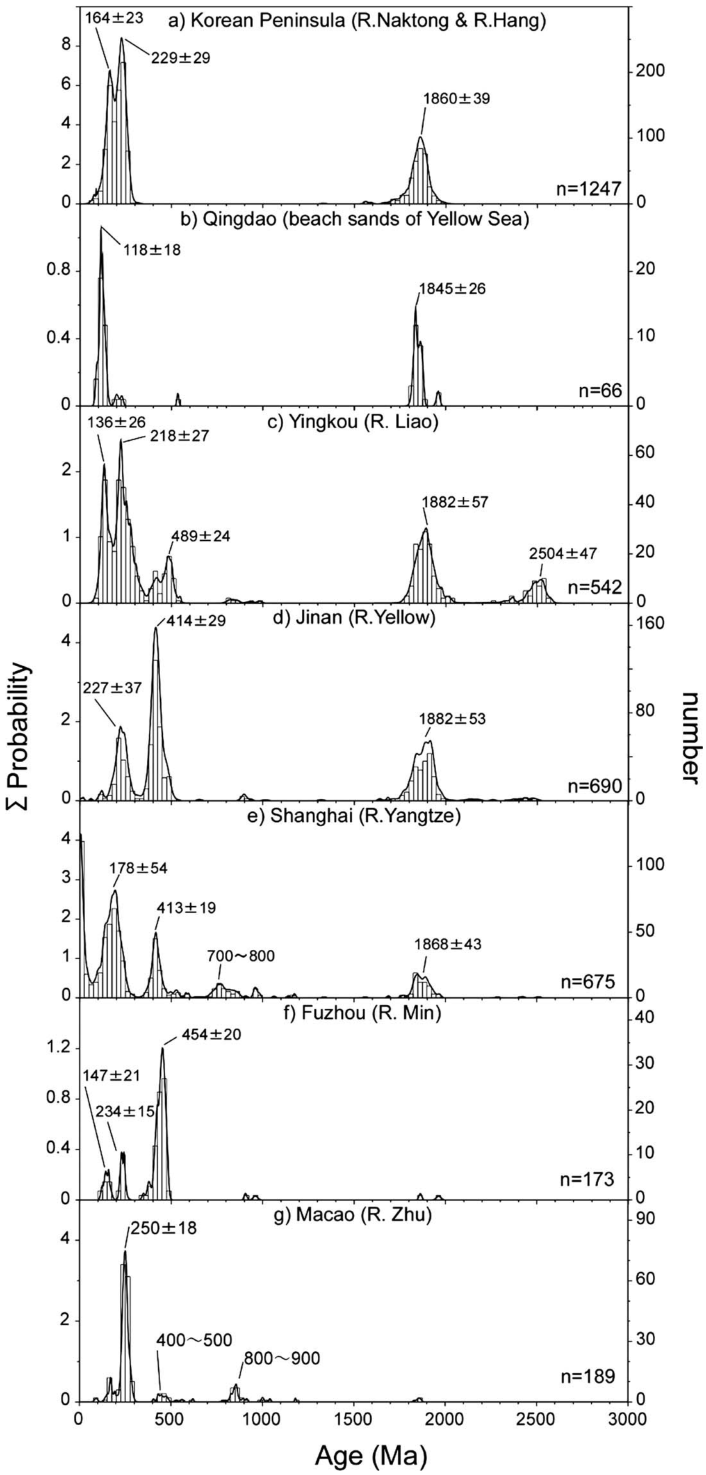


Fig. 11. Frequency and probability distribution diagrams of monazite ages in the sands collected along the East Asian continental margin (Fig. 7 of Yokoyama *et al*. 2007). Numerical value (n) denotes the number of analyzed monazite grains.

Early Cretaceous sediments.

The age patterns from the three islands, Busuanga, Mindoro, and Panay, on the Palawan microcontinent show simple bimodal distribution with clusters at 150–270 Ma and 1800–1950 Ma. As the data from Panay Island are too minor to discuss a peak position, more detailed comparisons were done for data from both the Busuanga and Mindoro islands. Roughly three peaks are recognized in the data from Busuanga and Mindoro islands. They are ca. 180 Ma, 240 Ma, and 1870 Ma. In comparison of these data with the data from the sands from the Asian continent, data younger than 150 Ma in the latter are excluded because such young monazites were absent at the time of the deposition of the Jurassic to Early Cretaceous sandstones.

On the Indochina Peninsula, age patterns are characterized by a strong peak at 250 Ma and a subordinate peak at 450 Ma (Yokoyama and Tsutsumi, 2008: Yokoyama *et al*., 2010). Data around 180 Ma and 1870 Ma are negligible. The southern coastal area of China- notably Guangdong and Fujian provinces- is the most probable candidate from where the Palawan microcontinent migrated during the Oligocene-Early Miocene. In the Guangdong Province, two rivers, the Zhu and Han rivers, cut through the coastal area of the continent. Age patterns of sands collected from eastern Asia are reproduced in Figure 11 (Yokoyama *et al*., 2007). The Zhu River is characterized by a strong peak at 250 Ma with small clusters at 400–500 Ma and 800–900 Ma. The Han River has three peaks at 155 Ma, 230 Ma, and 440 Ma. In both rivers, no visible peak is recognized at 1800–1900 Ma. The Min and Jiulong rivers in the Fujian Province are also characterized by peaks at 430–450 Ma and 230 Ma. Monazite with 1800–1900 Ma is scarce in both the rivers. None of the recent sands collected from the Indochina Peninsula and the southern coast of China show an age pattern similar to those observed in the Jurassic to Early Cretaceous sandstones on the Palawan microcontinenet. It indicates that the Indochina Peninsula and the southern coastal region of China could not have been the provenance area for sandstones on the Palawan microcontinenet.

Yangtze and Yellow rivers have huge drainage basins. The former has strong peaks at 180 Ma, 410 Ma, and 1870 Ma with a subordinate peak at 700–800 Ma. The latter has a strong peak at 410 Ma with subordinate peaks at 230 Ma and 1880 Ma. As both the rivers are characterized by a strong peak at 410 Ma, their drainage basins are not appropriate candidates for the sandstones in the Palawan sandstones.

The Korean Peninsula has a bimodal pattern with clusters at 150–300 Ma and 1800–2000 Ma (Fig. 11). Monazite with ages from 300 Ma to 1700 Ma is scarce. Peak positions are 164±23 Ma, 229±29 Ma, and 1860±39 Ma. The bimodal nature and peak positions are well consistent with those from the sandstones in the Palawan microcontinent. The Jurassic to Cretaceous sandstones in the subduction complex from the Japanese islands also have a bimodal age pattern. Yokoyama *et al*. (2000) concluded that the detrital monazites in the Japanese Islands were derived from the Korean Peninsula. Zamoras and Matsuoka (2001) concluded that the Jurassic-Early Cretaceous chert-siliceous shale–clastic sequence on Busuanga Island is similar to those from the Japanese Islands. Andal *et al*. (1968) also discussed the similarity in Jurassic fossils from the Mindoro Island with those on the Japanese Islands. Hence, it is not ridiculous to conclude that detrial monazites in the Jurassic to early Cretaceous sandstones on the Palawan microcontinent were parentally derived from the Korean Peninsula or surrounding areas. As for the other probable candidates, there are coastal areas near the Shandong Peninsula and Zhejiang Province. In the Shandong Peninsula, monazite age is bimodal with peak ages at 118±18 Ma and 1845±26 Ma. In the Zhejiang Province, the age pattern from the Ou River has a strong peak at 242±19 Ma and subordinate peaks at 117±29 Ma and 1854±36 Ma. Although younger monazites in both areas should not be expected for the Jurassic–Early Cretaceous sandstones, the areas cannot be simply excluded as a contributor to the provenance for the sandstones on the Palawan microcontinent. The Korean Peninsula, Shangdong Peninsula, and Zhejian Province are located in the marginal part of the East China Sea. The sea with a continental crust is widely distributed, but there is no datum about monazite from the sea. The drainage systems of rivers in the East Asia region have changed with geological time. Assuming that giant rivers like the present Yangtze and Yellow rivers were not developed during the Jurassic to Early Cretaceous, the areas including the East China Sea, Korean Peninsula, Shangdong Peninsula, and Zhejian Province are probable candidates as a provenance for sandstones on the Palawan microcontinent. As the microcontinent was located at the southwestern part of Taiwan before the opening of the South China Sea, the migration from the probable depositional area around the East China Sea will be at least several hundred km.

Secondary monazite showing a texture of aggregate has a peak age at 101±14 Ma. Plutonic age with around 100 Ma has been reported from the coastal region of China (e.g. Zhou and Li, 2000; Fig. 7 & 11, this paper). Sandstone with such monazite is a well-solidified rock and has metamorphic minerals such as epidote and titanite. Hence, it is concluded that the age corresponds to the metamorphic event at the coastal zone of East Asia. As the distribution of such sandstone is sporadic on the island, the metamorphic event may not be regional but local-possibly hydrothermal or contact metamorphism.

Depositional conditions

In a subduction complex, the chert-siliceous shale-clastic sequence is a general succession. Chert is pelagic, and deep-sea sediment and siliceous shale are hemipelagic. Whereas sandstone is generally treated as terrigenous sediment. These facies changes are brought by gradual plate movement from a remote oceanic environment toward the subduction zone. Zamoras and Matsuoka (2001) treated the sandstones in Busuanga Island as a part of the chert-siliceous shale-clastic sequence. However, the sandstones on the Busuanga Island are different from those in the subduction complex on the Japanese Islands. They are mostly tuffaceous and loosely packed, different from arkose or quartzose, and well-solidified in the normal Jurassic subduction complex. Shallow marine or brackish sediment occurs in the Middle Busuanga belt, Upper Jurassic zone of the Zamoras and Matsuoka (2001). It is characterized by a bituminous shale layer with patches of coal, a sandstone layer with sand pipe, and possible traces of fossil. Such bituminous shale is commonly intercalated with shallow marine sandstone on Mindoro Island.

In the sandstone from the subduction complex, Ca-rich garnets dissolved as did those from Panay Island. Ca-rich garnet on Busuanga Island has been preserved similar to that in the shallow marine sandstone from Mindoro Island. In contrast with Mg-rich garnet on Panay Island, garnets in the sandstones from both Busuanga and Mindoro islands are Mg-poor. It shows that sediments on Panay Island were derived from a region including high-grade metamorphic rock, whereas the latter was supplied by a relatively restricted region including only low-grade metamorphic rock. The samples BA014 and BA 015 contain abundant spinel grains, and they are mostly derived from ocean-island basalt (Kamenetsky *et al*., 2001). As the monazite grains must be supplied from the continental region only, the spinel grains will be supplied locally from an uplifted or obducted oceanic island. In spite of some coincidences with the subduction complex, it is possible that the sandstones on Busuanga Island will be shallow marine sediments as well as fossiliferous sandstone on Mindoro Island. Some serious problems will remain if the sandstones were shallow marine sediment. One is an observation by BMG (1984) that tuff and tuffaceous sandstone are intercalated with minor thinly bedded chert, i.e. coexistence of shallow marine and pelagic sediments. The other is the occurrence of tuff and tuffaceous sandstone in three belts on Busuanga Island showing continuous volcanic eruption throughout the Jurassic to Early Cretaceous. Further field work and analyses may resolve these problems.

Conclusions

The heavy minerals in the sandstones from Busuanga, Mindoro, and Panay islands, i.e. the Palawan microcontinent, were studied to elucidate the provenance of the detrital minerals. Although more detailed analyses will be necessary to deduce the tectonic reconstruction of the microcontinent, the following conclusions or suggestions are obtained from this study:

1: Age pattern of detrital monazite in the microcontinent is bimodal with clusters of 150–270 Ma and 1800–1950 Ma. None of the recent sands collected from the Indochina Peninsula and southern coast of China shows an age pattern similar to those observed on the microcontinent. As the bimodal pattern is observed around the East China Sea, it is concluded that the sandstones were parentally formed near the sea. Before the opening of the South China Sea, the microcontinent had moved for several hundred km from northeast to southwest of Taiwan.

2: The sandstones on Busuanga Island are mostly tuffaceous and loosely packed. Dissolution of garnet is not as severe as that in the subduction complex. In one outcrop, bituminous shale with a coal patch occurs and is surrounded by sandstones with abundant sand pipes. These evidences show that the sandstones on Busuanga Island were probably formed under shallow marine conditions as well as the well-documented conditions on Mindoro Island.

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. We also thank Mr. W. Mago for his help of the sampling on the islands.

References

Andal, D. R., J. S. Esguerra, W. Hashimoto, B. P. Reyes & T. Sato, 1968. The Jurassic Mansalay Formation, Southern Mindoro, Philipinnes. *Geology and Paleontology of South East Asia*, **4**: 179–197.

Bureau of Mines and Geosciences (BMG), 1984. Geological maps of Busuanga Island: Sheet nos. 2956 I & II, 3056 III & IV.

Evans, J. A., J. I. Chisholm & M. J. Leng, 2001. How U-Pb detrital monazite ages contribute to the interpretation of the Pennine Basin infill. *Journal of Geological Society,* **158**: 741–744.

Fan, D., C. Li, K. Yokoyama, B. Zhou, B. Li, Q. Wang, S. Yang, B. Deng & G. Wu, 2004. Study on the age spectrum of monazites in Late Cenozoic stratum of the Yangtze River delta and the run-through time of the Yangtze River. *Science in China (D)*, **34**: 1015–1022 (in Chinese).

Garver, J. I., M. T. Brandon, M. Roden-Tice & P. J. J. Kamp, 1999. Exhumation history of orogenic highlands determined by detrital fission-track thermochronology. In: Ring, U., Brandon, M. T., Lister, G. S. and Willett, S. D. (eds.), *Exhumation processes: Normal Faulting, ductile flow and erosion,* pp. 283–304. *Geological Society, London*.

Hamilton, W., 1979. Tectonics of the Indonesian region. U.S. Geological Survey Professional paper **1078**: 1–345.

Hashimoto, W. & T. Sato, 1973. Geologic structure of North Palawan and its bearing on the geological history of the Philippines. In: Toriyama R. & Kobayashi T. (eds.), Geology and Paleontology of Southeast Asia, **13**: 145–61.

Holloway, N. H., 1982. North Palawan Block, Philippines, its relation to Asian mainland and role in evolution of South China Sea. *American Association of Petroleum Geologists Buletin,*. **66**: 1355–83.

Ireland, T. R., 1991. Crustal evolution of New Zealand: Evidence from age distributions of detrital zircons in Western Province paragneisses and Torlesse greywacke. *Geochimica et Cosmochimica Acta,* **56**:

911–920.

Isozaki, Y., E. A. Amiscaraye & A. Rillon, 1987. Permian, Triassic, and Jurassic bedded radiolarian cherts in North Palawan Block, Philippines: Evidence of Late Mesozoic subduction-accretion. *Journal of the Geological Society of the Philippines*, **41**: 79–93.

Kamenetsky, V. S., A. J. Crawford & S. Meffre, 2001. Factors controlling chemistry of magmatic soinel: an Empirical study of associated olivine, Cr-spinel and melt inclusions from primitive rocks. *Journal of Petrology,* **42**: 655–671.

Morton, A. C., 1984. Stability of detrital heavy minerals in Tertiary sandstones from the North Sea Basin. *Clay Minerals*, **19**: 287–308.

Morton, A. C., 1991. Geochemical studies of detrital heavy minerals and their application to provenance research. In: Morton, A. C., Todd, S. P. & Haughton, P. D. W. (eds.), *Developments in Sedimentary Provenance Studies,* pp. 31–45. Geological Society of London, Special Pubulication no. 57.

Pettijohn, F. J., 1941. Persistence of heavy minerals and geologic age. *Journal of Geology*, **49**: 610–625.

Santosh, M., K. Yokoyama, S. Biju-Sekhar & J. J. W. Rogers, 2003. Multiple tectonothermal events in the granulite blocks of southern India revealed from EPMA dating: implications on the history of supercontinents. *Gondwana Research*, **6**: 29–64.

Santosh, M., T. Morimoto & Y. Tsutsumi, 2006. Geochronology of the khondalite belt of Trivandrum Block, Southern India: Electron probe ages and implications for Gondwana tectonics. *Gondwana Research*, **9**: 261–278.

Suzuki, K., M. Adachi & T. Tanaka, 1991. Middle Precambrian provenance of Jurassic sandstone in the Mino Terrane, central Japan: Th-U-total Pb evidence from an electron microprobe monazite study. *Sedimentary Geology*, **75**: 141–147.

Taylor, B. & D. E. Hayes, 1980. The tectonic evolution of the South China basin. In: Hayes D. E. (ed.). The tectonic and geological evolution of Southeast Asian seas and islands. *Geophysical Monograph*, **23**: 89–104.

Tsutsumi, Y., K. Yokoyama, K. Terada & Y. Sano, 2003. SHRIMP U-Pb dating of detrital zircons in metamorphic rocks from northern Kyushu, western Japan. *Journal of Mineralogical and Petrological Sciences*, **98**: 220–230.

Yokoyama, K., K. Amano, A. Taira & Y. Saito, 1990. Mineralogy of silts from Bengal Fan. *Proceedings of Ocean Drilling Project, Science Results*, **116**: 69–73.

Yokoyama, K. & A. Goto, 2000. Petrological study of the Upper Cretaceous sandstones in the Izumi Group, Southwest Japan. *Memoirs of the National Science Museum*, **32**: 7–17.

Yokoyama, K. & Y. Saito, 2001. Provenance study of pre-Tertiary sandstones in the northern Kanto. *Memoirs of the National Science Museum*, **32**: 7–17.

Yokoyama, K., Y. Tsutsumi, C. S. Lee, J. J. S. Shen, C. Y. Lan & L. Zhao, 2007. Provenance study of Tertiary sandstones from the Western Foothills and Hsuehshan Range, Taiwan. *Bulletin of the National Museum of Nature and Science, Series. C*, **33**: 7–26.

Yokoyama, K. & Y. Tsutsumi, 2008. Reconnaissance study of monazite age from Southeast Asia. *Memoirs of the National Museum of Nature and Science*, 45: 139–148.

Yokoyama, K., Y. Tsutsumi, N. T. Nhung & P. Quynh, 2010. Age distribution of monazites from the nine rivers of Vietnam. *Memoirs of the National Museum of Nature and Science*, 46: 97–108.

Yumul, G. P. JR., C. B. Dimalanta, R. A. JR. Tamayo & R. C. Maury, 2003. Collision, subduction and accretion events in the Philippines: a synthesis. *The Island Arc*, **12**, 77–91.

Williams, I. S., 1998. U-Th-Pb geochronology by Ion Microprobe. *Reviews in Economic Geology*, **7**: 1–35.

Wyck, N. V. & M. Norman, 2004. Detrital zircon ages from Early Proterozoic quartzite, Wisconsin, support rapid weathering and deposition of mature quartz arenites. *Journal of Geology*, **112**: 305–315.

Zamoras, L. R. & A. Matsuoka, 2001. Malampaya Sound Group: a Jurassic-Early Cretaceous accretionary complex in the Busuanga Island, North Palawan Block (Philippines). *Journal of the Geological Society of Japan*, **107**: 316–36.

Zamoras, L. ion tectonics of the Calamian Islands, North Palawan Block (Philippines). *The Island Arc*, **13**: 506–519.

Zamoras, L. R., M. G. A. Montes, K. L. Queano, E. J. Marguez, C. B. Dimalnata, J. A. S. Gabo & G. P. Yumul, 2008. Buruanga peninsula and Antique Range: Two contrasting terranes in northwest Panay, Philippines featuring an arc-continent collision zone. *The Island Arc*, **17**: 443–457.

Zhou, X. and Li, W. X. 2000. Origin of Late Mesozoic igneous rocks of southeastern China: implications for lithosphere subduction and underplating of mafic magma. *Tectonophysics*, **326**: 269–287.

フィリピンのパラワン地塊のジュラ紀―前期白亜紀の砂岩の供給源について

横山一己・堤之恭・加瀬友喜・Karlo L. Queaño・Aguilar Yolanda M.

パラワン地塊は，漸新世から前期中新世にかけて中国南部から分離したと考えられている．このパラワン地塊中の砂岩の供給源を調べることにより，ジュラ紀―前期白亜紀にどこで形成されたかが判明できる．砂岩中のモナズ石の年代測定では，140–260 Ma と 1800–2000 Ma の 2 つの集団を持つ分布が得られた．このような年代分布は，現在の中国南部やインドシナにはなく，東シナ海周辺の地域から知られているだけである．パラワン地塊は，ジュラ紀―前期白亜紀に現在の東シナ海近辺で形成されたものであることが判明した．この地塊は，漸新世前期には中国南部に存在したと考えられることから，形成された場所からは数百 km 西に移動したと推定できる．