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Thematic Article

Detrital zircon geochronology of the Cretaceous Sindong Group, Southeast Korea: Implications for depositional age and Early Cretaceous igneous activity

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Abstract The Sindong Group forms the lowermost basin-fill of the Gyeongsang Basin, the largest Cretaceous nonmarine basin located in southeastern Korea, and comprises the Nakdong, Hasandong, and Jinju Formations with decreasing age. The depositional age of the Sindong Group has not yet been determined well and the reported age ranges from the Valanginian to Albian. Detrital zircons from the Sindong Group have been subjected to U–Pb dating using laser ablation inductively coupled plasma mass spectrometry. The Sindong Group contains noticeable amounts of detrital magmatic zircons of Cretaceous age (138–106 Ma), indicative of continuous magmatic activity prior to and during deposition of the Sindong Group. The youngest detrital zircon age of three formations becomes progressively younger stratigraphically: 118 Ma for the Nakdong Formation, 109 Ma for the Hasandong Formation, and 106 Ma for the Jinju Formation. Accordingly, the depositional age of the Sindong Group ranges from the late Aptian to late Albian, which is much younger than previously thought. Lower Cretaceous magmatic activity, which supplied detrital zircons to the Sindong Group, changed its location spatially through time; it occurred in the middle and northern source areas during the early stage, and then switched to the middle to southern source areas during the middle to late stages. This study reports first the Lower Cretaceous magmatic activity from the East Asian continental margin, which results in a narrower magmatic gap (*ca* 20 m.y.) than previously known.

Key words: Cretaceous, depositional age, Gyeongsang Basin, magmatism, U–Pb zircon age.

INTRODUCTION

The Gyeongsang Basin, the largest Cretaceous nonmarine basin in Korea, was formed in an active continental margin setting caused by the subduction of the Paleo-Pacific (Izanagi) Plate beneath the East Asian continent. The basin-fill comprises sedimentary strata in the lower sequence and volcanic and plutonic rocks in the upper sequence. The lowermost Sindong Group is distributed in the western margin of the Gyeongsang Basin (Fig. 1). Although the Gyeongsang Basin sediments were extensively studied for stratigraphic classification and correlation, the depositional age of the Sindong Group is generally known as the Early Cretaceous, but is still poorly defined in detail. The depositional age of the sediment fill is important to understand the tectonic history of the basin formation and paleogeographic reconstruction. This is because, in the East Asian continental margin, the timing of basin formation and its subsequent evolution is closely related to the subduction processes of the Paleo-Pacific Plate beneath the East Asian continent.

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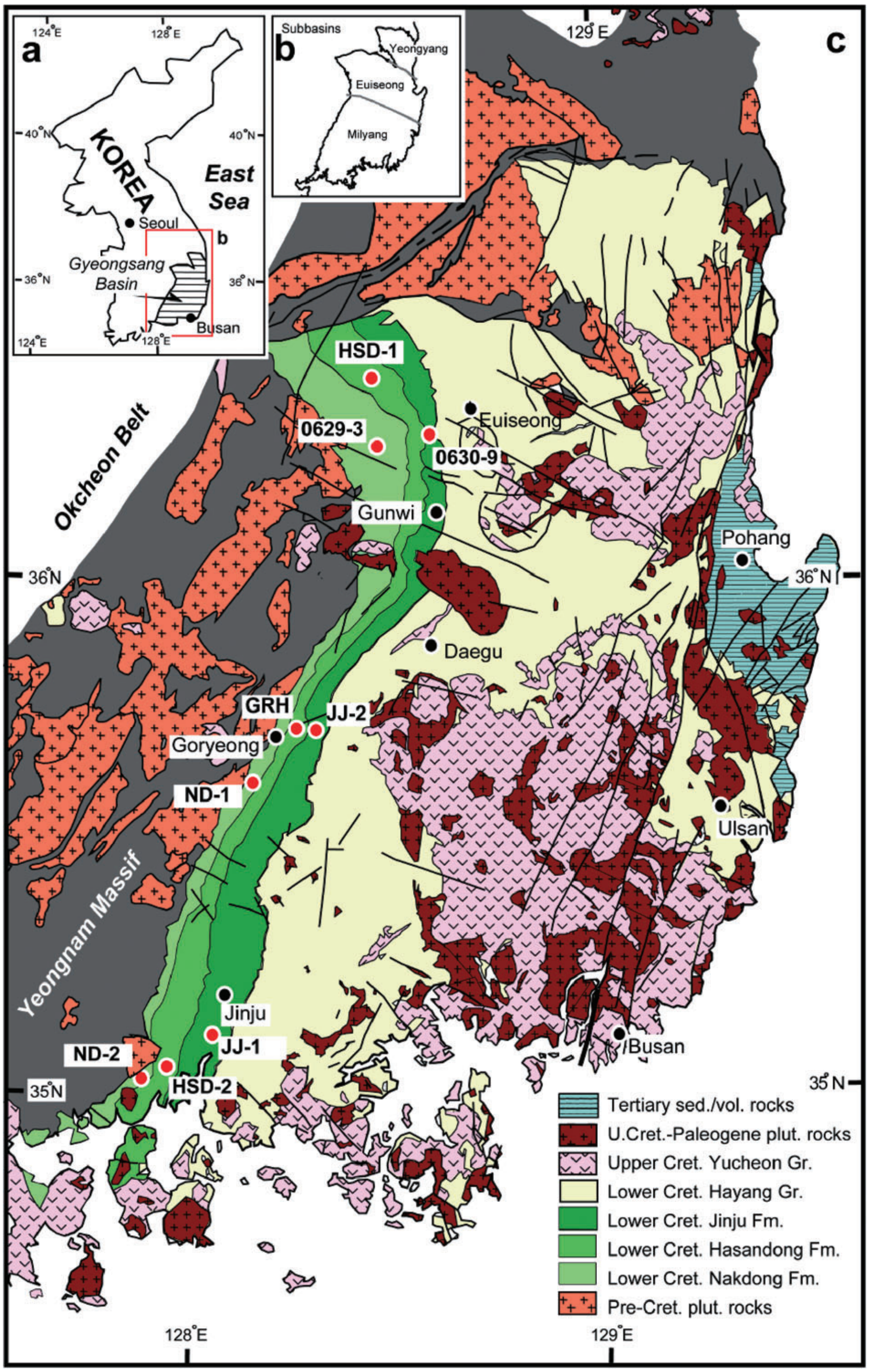

Fig. 1 (a) Location of the Gyeongsang Basin. (b) Subbasins of the Gyeongsang Basin. (c) Geological map of the western half of the Gyeongsang Basin with sampling localities (modified after Lee and Lee, 2000).

Based on the analyses of U–Pb sphene ages of Mesozoic granitoids combined with the existing crystallization ages of Phanerozoic granitoids, Sagong *et al.* (2005) presented three episodes of Mesozoic magmatism in South Korea: the Triassic (248–210 Ma), Jurassic (197–158 Ma), and Late Cretaceous–early Paleogene (110–50 Ma). They noted a significant magmatic gap of about 50 m.y. from 160 to 110 Ma in South Korea. Tectonically, the period of the highly oblique subduction of the Izanagi Plate in the Early Cretaceous is interpreted to coincide with that of magmatic gap of South Korea (Sagong *et al.* 2005). Due to such a magmatic gap, it became difficult to constrain the timing of basin formation and age of the basin fills, especially of the Early Cretaceous. The means available for age determination of nonmarine basin-fills in this period remains in paleontological and paleomagnetic data. However, biostratigraphic resolution of fossils is rather low and identification of a polarity chron needs an independent chronometer like radiometric ages of volcanic rocks or volcanic ashes associated with basin fills. When neither technique is successful, U–Pb ages of detrital zircon populations offer an alternative means available for constraining the timing of deposition of the basin-fills. Provided there has been no disturbance of the U–Pb system, the youngest igneous crystallization dates obtained on detrital zircons from a sedimentary rock sample will provide a maximum age for host sediment deposition (Nelson 2001; Dunn *et al*. 2005).

The purposes of this study are to infer the depositional age of the Sindong Group using detrital zircon U–Pb dating by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) and to identify contemporary source regions for sediment influx into the Gyeongsang Basin. Then using these data, we discuss correlations with presumed coeval sedimentary basins in the adjacent regions, the depositional age of the overlying Hayang Group, and the Cretaceous igneous activity in South Korea considering the tectonic setting of that time.

GEOLOGICAL SETTING

During the Cretaceous, the eastern margin of the Asian continent, including the Korean Peninsula, was an Andean-type continental margin (Choi 1986a; Watson *et al*. 1987). At this time, older Permian to earliest Cretaceous accretionary complexes made up the eastern margin of the Asian continent (Taira *et al*. 1989; Isozaki 1997), while further inboard a belt of Jurassic calc-alkaline arc granite dominated the paleogeographic setting (Isozaki 1997). From the Early Cretaceous, the Izanagi Plate began to move northward relative to East Asia and subducted highly oblique to the East Asian continental margin (Engebretson *et al*. 1985; Otsuki 1992; Maruyama *et al*. 1997; Taira 2001). This oblique convergence initiated a left-lateral slip along northeast-striking faults in the continental arcs including South Korea (Lee 1999a) and Japan (Otsuki 1992; Otoh & Yanai 1996; Taira 2001). In South Korea, about 10 small Cretaceous pull-apart basins developed along these left-lateral faults (Lee 1999a) and east-trending fold structures associated with these left-lateral faults suggests a north–south regional compression in the Early Cretaceous (Cluzel 1992; Kim 1996). Although the Gyeongsang Basin is presumed to have formed along with these pull-apart basins under the similar tectonic setting, the earliest development of the Gyeongsang Basin was reinterpreted to be of rift origin associated with plume-related magmatism (Okada 1999, 2000; Chang 2002). However, a recent study suggests that the Gyeongsang Basin was initiated by north–south left-lateral regional simple shear as a wrench tectonic system due to highly oblique subduction of the Izanagi Plate (Hwang *et al*. 2008). Arc-related igneous activities and accretion mostly related to the orthogonal subduction were minimal during this early developmental phase of basin formation in the East Asian continental margin (Maruyama *et al*. 1997).

Cretaceous rocks in the Gyeongsang Basin are divided into four groups based on volcanism and plutonism (Chang 1975). They are, from oldest to youngest, the Sindong, Hayang, Yucheon, and the Bulkuksa intrusive Groups. The lowermost Sindong Group was deposited along the western margin of the basin, termed the Nakdong Trough (Chang 1987). The Sindong Group is underlain unconformably by crystalline basement on the western and northern sides and is overlain conformably by the Hayang Group on the eastern side. The Sindong Group is 2–3 km thick, and consists mainly of sandstone and mudstone, with minor amounts of conglomerate and marl. It is subdivided, on the basis of lithological features including rock color, into the Nakdong (alluvial fan to fluvial deposits), Hasandong (fluvial deposits), and Jinju (lacustrine deposits) Formations with decreasing age. The Nakdong Formation is about 550 m thick, and thickens northwards. The lowermost part of the formation consists of mid-fan conglomerates overlain by distal-fan sandstones intercalated by dark gray mudstones and black shales. The alluvial fan deposits grade upwards into fluvial plain deposits, which are composed mainly of alternating beds of channel sandstones and inter-channel dark gray mudstones and siltstones. The Hasandong Formation, approximately 1100 m thick, is similar to the uppermost part of the Nakdong Formation in that it consists of alternating channel sandstones and inter-channel fine deposits, but shows characteristic red beds containing calcareous nodules (Lee 1999b). The lacustrine Jinju Formation is about 1200 m thick, and is made up mainly of lacustrine dark gray to black shales and channel sandstones. Paleocurrent studies indicate that the mean direction of sediment transport was toward the east and southeast (Chang & Kim 1968; Koh 1986). Sindong Group sediments are interpreted as the prevolcanic stage deposits that have been derived from Precambrian gneisses and Jurassic granitic rocks of the Yeongnam Massif, located to the west and northwest (Koh 1974). However, the upper half of the Jinju Formation contains a significant amount of volcanic detritus (Choi 1986b; Noh & Park 1990; Lee & Lim 2008). Deposition of the Hayang Group accompanied the basin extension to the east along with sporadic volcanism in and around the basin (Chang 1970, 1987). Hayang Group sediments were derived from both the volcanic and plutonic–metamorphic provenances (Lee & Lee 2000). During this interval, the Gyeongsang Basin was divided into three subbasins with different subsidence histories and sedimentary environments. They are from north to south the Yeongyang, Euiseong, and Milyang subbasins (Fig. 1b; Chang 1970, 1975). Consequently, different lithostratigraphic classifications have been applied for the Hayang Group in these subbasins.

PREVIOUS STUDIES ON DEPOSITIONAL AGE OF SINDONG GROUP

The suggested depositional age of the Sindong Group ranges widely from the Late Jurassic to late Aptian. In the first half of the 20th Century, based on pollen studies Yabe (1905) suggested that the Sindong Group was deposited in the Late Jurassic. Tateiwa (1929) also studied pollens in the Sindong Group, but he suggested that it was deposited during the Late Jurassic to Early Cretaceous. Later, Kobayashi and Suzuki (1936) reinterpreted that the Sindong Group was deposited in the Early Cretaceous. Yang (1974, 1989) studied nonmarine mollusks from the Sindong Group and suggested that the Sindong Group was deposited during the Aptian to Albian. Spore and pollen studies done by Fontaine and Poumot (1980) suggested that the Sindong Group was deposited during the Early Cretaceous. Subsequent studies on Charophyta (Seo 1985; Choi 1987, 1989) and spores and pollen (Choi 1985; Choi & Park 1987) suggested more specifically that the Sindong Group was deposited during the late Valanginian–Barremian. Based on extensive stratigraphic and paleontological analyses in the Gyeongsang Basin, Chang (1975) interpreted that the Sindong Group was deposited during the Barremian to early Aptian. All these paleontological studies reveal their limit of chronological information due to coarse resolution of biostratigraphic data. Later studies on non-paleontological studies revealed more detailed chronological information. Doh *et al.* (1994) studied paleomagnetism of the Sindong Group and suggested that the Sindong Group was deposited in the post-early Aptian based on the observation of long Cretaceous normal polarity geomagnetic zone. From a volcanic pebble of the Silla Conglomerate in the lower part of the overlying Hayang Group, Kim *et al.* (2005) obtained an $^{40}Ar/^{39}Ar$ hornblende age of 113.4 ± 2.4 Ma, suggestive of the depositional age of the Sindong Group being younger than the late Aptian. Sano *et al.* (2006) determined a U–Pb age of 115 ± 10 Ma (early Aptian) of a dinosaur tooth from the Hasandong Formation. Considering that this radiometric age of the dinosaur tooth represents the diagenetic age, the depositional age of the host Hasandong Formation would be slightly older than the early Aptian.

METHODS

To interpret the spatial and temporal variations in the contemporary igneous sources for the Gyeongsang Basin, the distribution area of the Sindong Group was subdivided into three regions: from north to south, the Gunwi area in the Euiseong Subbasin and the Goryeong and Jinju areas in the Milyang Subbasin (Fig. 1). For this study three sandstone samples from each formation (one sandstone sample from each formation at each area) were collected. A total of nine sandstone samples were processed using conventional methods for crushing and milling. Zircon grains (63–125 μm) were first concentrated using a combination of Wilfley table separation, magnetic separation, and heavy liquid techniques, and then collected by hand-picking. More than 300 zircon grains were obtained from each sandstone sample. One hundred zircon grains from each sandstone sample were randomly selected and mounted in PFA Teflon sheet and/or petro-epoxy resin. In total 900 zircon grains were prepared for U–Pb zircon age dating. Then they were polished, cleaned and gold-coated. To obtain internal structures, cathodoluminescence images of zircon grains were examined under a scanning electron microscope (JEOL JSM-5400).

The LA-ICP-MS used in this study is Thermo Elemental PlasmaQuad 3 housed at the Earthquake Research Institute, University of Tokyo. This instrument is equipped with S-option interface and a CHICANE ion lens (Orihashi *et al.* 2003). The laser ablation system is a New Wave UP213 system, which uses a frequency-quintupled Nd–YAG at 213 nm wavelength. The analytical procedure was described by Orihashi *et al.* (2008). The carrier gas was He and small amount of N_2 gases (0.8 mL/min) was mixed into the carrier gas. Operational settings of ICP conditions, such as torch position, gas flow rates or lens settings were optimized to maximize ^{208}Pb signal intensity by laser ablation of an SRM610 glass standard. The instrument sensitivity obtained in this study was 570–2300 cps/μg per g for Pb with the ablation pit size of 30 μm, energy density of 11–13 J/cm^3, pulse width of 4 ns nominal and pulse repetition rate of 10 Hz. Single-spot ablation was achieved by a 3-s pre-ablation and 20 s for data acquisition. A single spot per grain was analyzed for the majority of zircon grains. The inter-element fractionation during the analysis was monitored by analyzing a fragment of the zircon 91500 standard, which has a concordant isotope-dilution thermal ionization mass spectrometry age of 1062.4 ± 0.4 Ma (Wiedenbeck *et al.* 1995). The standard was analyzed once for every five unknowns, so the quality of the analyses was closely controlled.

The Pb isotopic ratios were corrected for common Pb using the measured ^{204}Pb, assuming an initial Pb composition according to Stacey and Kramers (1975) and uncertainties of 1.0%, 0.3%, and 2.0%, respectively, for ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, and ^{208}Pb/^{204}Pb. Data processing was carried out using the ISOPLOT program (Ludwig 2003). Common Pb was subtracted from analyzed ^{204}Pb. Detrital zircons constitute a mixture of grains of different ages and the time for Pb loss is difficult to assess with confidence. Accordingly, ages with >15% discordance or >10% reverse discordance are considered unreliable and were not used.

RESULTS

Among about 900 zircon grains analyzed, about 670 zircon grains yielded concordant or slightly discordant Archean to Cretaceous U–Pb ages, of which Cretaceous U–Pb ages were derived from 48 zircon grains. Out of nine sandstone samples, one Nakdong (ND-2) and one Hasandong (HSD-1) sandstone sample did not yield Cretaceous detrital zircons. Analytical results are listed in Table 1. Cretaceous detrital zircon grains show euhedral prismatic crystal morphology. Also, the studied zircon grains show well-developed fine-scale oscillatory growth zoning (Fig. 2). Cretaceous detrital zircons have U–Pb ages ranging from 137.9 ± 7.1 to 106.2 ± 3.7 Ma. Nakdong sandstones have four Cretaceous zircon ages (138–118 Ma), Hasandong sandstones 18 Cretaceous zircon ages (126–109 Ma), and Jinju sandstones contain 26 Cretaceous zircon ages (134–106 Ma). The U–Pb data are shown on Pb/U concordia diagrams in Figure 3. All zircons analyzed have Th/U ratios larger than 0.2 (Table 1), indicating that they are of igneous origin (Vavra *et al.* 1999; Hartmann & Santos 2004).

The youngest Cretaceous zircon age is 118.0 ± 3.0 Ma for the Nakdong Formation, 109.0 ± 3.4 Ma for the Hasandong Formation, and 106.0 ± 1.9 Ma for the Jinju Formation (Fig. 2). Spatially, the youngest zircon of the Nakdong Formation occurs in the Goryeong area, that of the Hasandong Formation in the Jinju area, and that of the Jinju Formation in the Gunwi area.

INTERPRETATION AND DISCUSSION

DEPOSITIONAL AGE OF SINDONG GROUP

The depositional age of the Sindong Group can be constrained by the youngest age of the detrital zircons. Although the youngest zircon age of the Jinju Formation agrees within error with that of the Hasandong Formation, the youngest age becomes progressively younger up-sequence. Accordingly, the maximum depositional age of the Sindong Group is late Aptian and it seems that deposition of the Sindong Group lasted until the end of the Albian. This newly proposed depositional age is much younger than any of the ages suggested so far, but generally agrees with that of Yang (1974, 1989). The diagenetic age of dinosaur tooth from the Hasandong Formation (Sano *et al.* 2006) is slightly older than the proposed age of this study, but generally fits within the new chronological frame.

Because the Gyeongsang Basin contrasts with other smaller pull-apart basins in scale and shape, it was generally thought that the Gyeongsang Basin formed earlier than these pull-apart basins. Most basin-fills of these pull-apart basins were correlated with the upper Hayang and Yucheon Groups of the Gyeongsang Basin, partly based on radiometric ages of associated volcanic rocks in

Table 1 U–Pb isotopic data for zircon grains determined by LA-ICP-MS

Sample Name	Th/U	$^{206}Pb_c$† (%)	$^{207}Pb/^{206}Pb$	Error 2σ	$^{206}Pb/^{238}U$	Error 2σ	$^{207}Pb/^{235}U$	Error 2σ	Disc‡ (%)	$^{238}U–^{206}Pb$ age (Ma)	Error 2σ	$^{235}U–^{207}Pb$ age (Ma)	Error 2σ
Jinju Fm. ($n = 26$)													
0630-9-92	0.85	n.d	0.0547	± 0.0015	0.0166	± 0.0003	0.1251	± 0.0042	−7.4	106.0	± 1.9	119.7	± 4.0
JJ2-26	2.13	n.d	0.0516	± 0.0038	0.0195	± 0.0007	0.1388	± 0.0113		124.6	± 4.4	132.0	± 10.8
JJ2-41	1.05	n.d	0.0505	± 0.0039	0.0190	± 0.0006	0.1322	± 0.0111		121.3	± 3.9	126.1	± 10.5
JJ2-47	1.79	n.d	0.0481	± 0.0055	0.0178	± 0.0008	0.1179	± 0.0144		113.5	± 4.8	113.1	± 13.8
JJ2-51	1.19	n.d	0.0480	± 0.0025	0.0180	± 0.0007	0.1191	± 0.0079		115.0	± 4.6	114.3	± 7.6
JJ2-58	1.04	n.d	0.0495	± 0.0040	0.0181	± 0.0007	0.1237	± 0.0113		115.8	± 4.7	118.4	± 10.8
JJ2-67	1.81	n.d	0.0535	± 0.0027	0.0178	± 0.0005	0.1313	± 0.0077	−0.5	113.8	± 3.5	125.2	± 7.4
JJ2-68	2.16	n.d	0.0442	± 0.0036	0.0184	± 0.0006	0.1124	± 0.0098		117.7	± 3.8	108.2	± 9.4
JJ2-70	0.81	n.d	0.0554	± 0.0052	0.0166	± 0.0006	0.1269	± 0.0128		106.2	± 3.7	121.3	± 12.2
JJ2-74	2.13	n.d	0.0494	± 0.0040	0.0173	± 0.0004	0.1179	± 0.0101		110.5	± 2.9	113.1	± 9.6
JJ2-76	2.27	n.d	0.0562	± 0.0027	0.0177	± 0.0004	0.1375	± 0.0072	−7.1	113.4	± 2.5	130.8	± 6.8
JJ2-79	0.89	n.d	0.0516	± 0.0038	0.0174	± 0.0004	0.1234	± 0.0097		110.9	± 2.8	118.1	± 9.3
JJ2-83	0.92	n.d	0.0514	± 0.0021	0.0199	± 0.0007	0.1408	± 0.0076		126.8	± 4.4	133.7	± 7.2
JJ2-87	1.26	n.d	0.0545	± 0.0035	0.0171	± 0.0006	0.1282	± 0.0095	−0.4	109.0	± 4.0	122.5	± 9.1
JJ2-98	0.99	0.24	0.0483	± 0.0027	0.0181	± 0.0008	0.1204	± 0.0086		115.6	± 5.1	115.4	± 8.2
JJ1-6	0.25	n.d	0.0501	± 0.0016	0.0180	± 0.0002	0.1244	± 0.0042		115.1	± 1.6	119.1	± 4.0
JJ1-9	1.26	n.d	0.0490	± 0.0024	0.0180	± 0.0006	0.1213	± 0.0070		114.7	± 3.5	116.2	± 6.7
JJ1-13	1.54	n.d	0.0450	± 0.0046	0.0190	± 0.0007	0.1177	± 0.0128		121.2	± 4.2	113.0	± 12.3
JJ1-18	1.08	n.d	0.0492	± 0.0017	0.0176	± 0.0006	0.1196	± 0.0060		112.7	± 4.0	114.7	± 5.7
JJ1-35	1.31	n.d	0.0499	± 0.0028	0.0171	± 0.0007	0.1177	± 0.0082		109.4	± 4.3	113.0	± 7.8
JJ1-38	2.09	2.26	0.0479	± 0.0020	0.0180	± 0.0011	0.1191	± 0.0087		115.2	± 6.9	114.3	± 8.4
JJ1-50	1.64	n.d	0.0464	± 0.0030	0.0171	± 0.0007	0.1096	± 0.0082		109.5	± 4.2	105.6	± 7.9
JJ1-52	1.31	n.d	0.0508	± 0.0057	0.0184	± 0.0008	0.1290	± 0.0154		117.6	± 4.9	123.2	± 14.7
JJ1-82	1.16	n.d	0.0567	± 0.0031	0.0194	± 0.0010	0.1515	± 0.0117	−1.3	123.8	± 6.7	143.2	± 11.1
JJ1-91	1.93	n.d	0.0514	± 0.0017	0.0192	± 0.0009	0.1360	± 0.0079		122.5	± 5.9	129.5	± 7.6
JJ1-96	1.35	n.d	0.0524	± 0.0017	0.0183	± 0.0009	0.1320	± 0.0079		116.7	± 5.9	125.9	± 7.6
Hasandong Fm. ($n = 18$)													
GRH-23	0.85	n.d	0.0505	± 0.0013	0.0172	± 0.0003	0.1201	± 0.0038		110.1	± 2.0	115.1	± 3.6
GRH-24	0.74	n.d	0.0488	± 0.0028	0.0176	± 0.0004	0.1187	± 0.0072		112.7	± 2.4	113.9	± 6.9
GRH-44	1.07	n.d	0.0477	± 0.0028	0.0183	± 0.0007	0.1207	± 0.0085		117.1	± 4.7	115.7	± 8.2
GRH-46	1.56	n.d	0.0562	± 0.0041	0.0189	± 0.0004	0.1464	± 0.0111	−4.4	120.6	± 2.3	138.7	± 10.5
GRH-50	3.08	n.d	0.0554	± 0.0055	0.0188	± 0.0004	0.1435	± 0.0146		120.1	± 2.5	136.1	± 13.9
GRH-55	1.20	n.d	0.0462	± 0.0038	0.0198	± 0.0004	0.1263	± 0.0107		126.6	± 2.4	120.8	± 10.2
GRH-93	1.65	n.d	0.0435	± 0.0037	0.0187	± 0.0006	0.1122	± 0.0101		119.5	± 3.9	108.0	± 9.7
HSD2-1	0.52	n.d	0.0476	± 0.0015	0.0174	± 0.0010	0.1141	± 0.0073		111.2	± 6.1	109.7	± 7.0
HSD2-18	0.45	n.d	0.0522	± 0.0021	0.0197	± 0.0006	0.1415	± 0.0072		125.5	± 3.9	134.4	± 6.8
HSD2-21	0.59	1.88	0.0392	± 0.0024	0.0176	± 0.0006	0.0953	± 0.0065		112.6	± 3.6	92.4	± 6.3
HSD2-22	0.53	n.d	0.0505	± 0.0022	0.0171	± 0.0005	0.1189	± 0.0064		109.0	± 3.4	114.1	± 6.1
HSD2-24	0.52	n.d	0.0468	± 0.0023	0.0174	± 0.0005	0.1124	± 0.0066		111.4	± 3.5	108.2	± 6.3
HSD2-25	0.57	n.d	0.0497	± 0.0021	0.0176	± 0.0005	0.1205	± 0.0062		112.2	± 3.5	115.5	± 6.0
HSD2-44	3.04	n.d	0.0446	± 0.0057	0.0193	± 0.0007	0.1185	± 0.0159		122.9	± 4.7	113.7	± 15.2
HSD2-48	0.96	n.d	0.0503	± 0.0031	0.0191	± 0.0010	0.1325	± 0.0106		122.1	± 6.3	126.4	± 10.1
HSD2-50	1.20	n.d	0.0498	± 0.0039	0.0188	± 0.0010	0.1289	± 0.0121		119.9	± 6.3	123.1	± 11.6
HSD2-56	0.28	n.d	0.0486	± 0.0024	0.0179	± 0.0009	0.1202	± 0.0085		114.6	± 5.8	115.3	± 8.1
HSD2-57	1.26	n.d	0.0497	± 0.0021	0.0186	± 0.0009	0.1277	± 0.0085		119.1	± 6.0	122.0	± 8.1
Nakdong Fm. ($n = 4$)													
0629-3-55	0.81	n.d	0.0527	± 0.0018	0.0191	± 0.0005	0.1389	± 0.0062	−0.5	122.0	± 3.5	132.0	± 5.9
ND1-8	0.80	n.d	0.0477	± 0.0026	0.0216	± 0.0011	0.1421	± 0.0107		137.9	± 7.1	134.9	± 10.2
ND1-46	0.41	0.02	0.0539	± 0.0019	0.0191	± 0.0005	0.1422	± 0.0061	−3.3	122.2	± 2.9	135.0	± 5.8
ND1-54	1.47	0.10	0.0476	± 0.0020	0.0185	± 0.0005	0.1212	± 0.0060		118.0	± 3.0	116.2	± 5.7

† $^{206}Pb_c$, percentage of ^{206}Pb contributed by common Pb on the basis of ^{204}Pb. Value of common Pb was assumed by Stacey and Kramers (1975) model.; n.d. no detection of ^{204}Pb. ‡ Degree of discordance (%); negative numbers and blanks show normal discordant and concordance within 2σ of the analytical error, respectively.

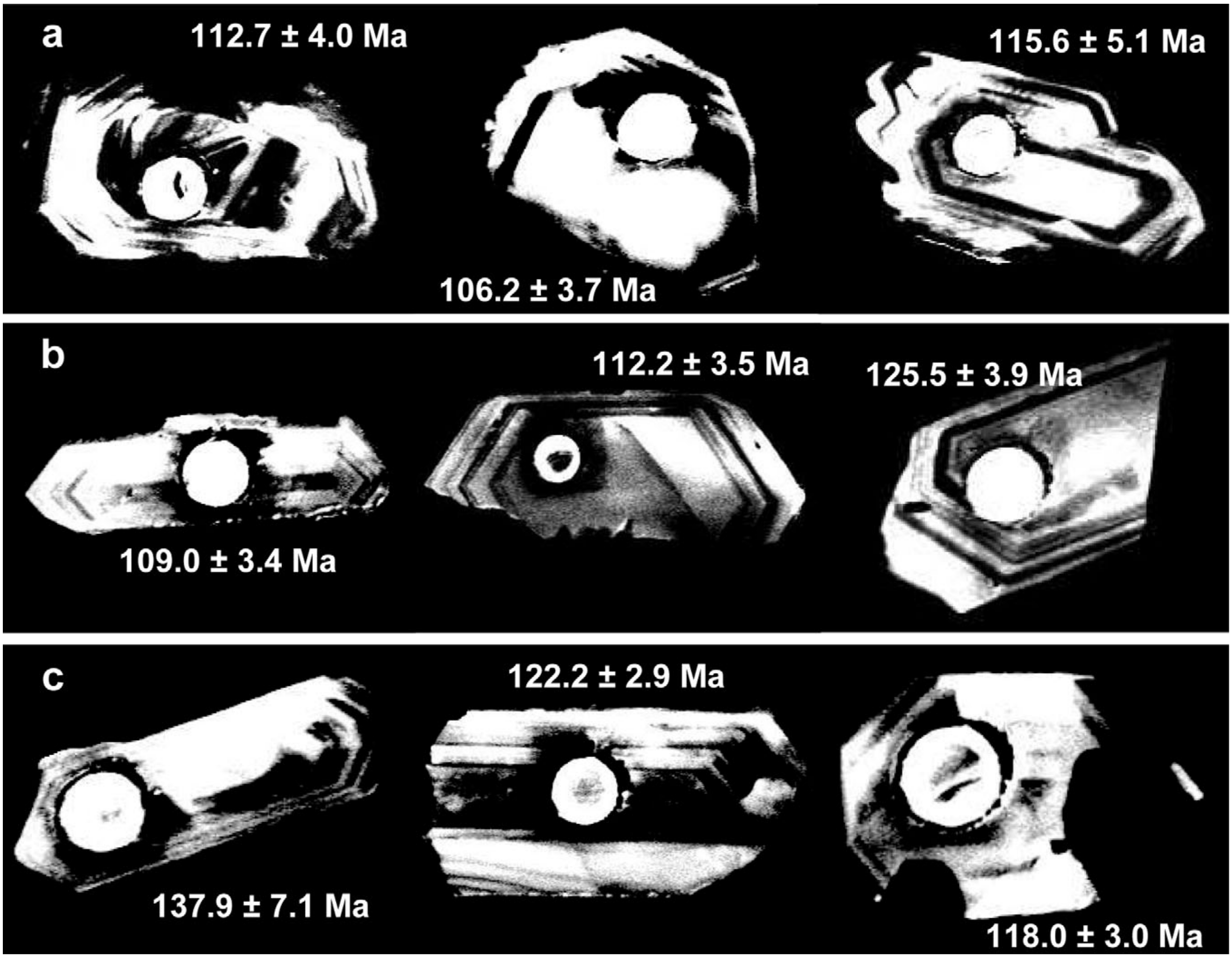

Fig. 2 Representative cathodoluminescence images of detrital zircons from the Sindong Group. Numbers in zircon grains represent LA-ICP-MS U–Pb ages. (a) Jinju Formation, (b) Hasandong Formation, and (c) Nakdong Formation.

these basins (cf. Hwang *et al*. 2008). However, considering that the newly interpreted depositional age of the Sindong Group is slightly earlier or coeval with depositional ages of some of the pull-apart basins, this study proposes that the Gyeongsang Basin seems to have formed during the similar time period with these pull-apart basins, but with different basin formation mechanism.

Paleogeographically, the Kanmon Basin located in Southwest Japan has been closely correlated with the Gyeongsang Basin, and the Wakino Subgroup of the Kanmon Basin was suggested to be correlative to the Sindong Group in terms of lithostratigraphy and depositional age. The Wakino Subgroup reaches 1300 m in thickness and has been dated as the late Valanginian–Barremian based on fossil evidence (Ota 1960). Ishiga *et al*. (1997) and Asiedu *et al*. (2000) interpreted that the Wakino Subgroup shared the same provenances with the Sindong Group and suggested that both the Gyeongsang and Kanmon Basins might have formed a single depositional basin. Although such a paleogeographic setting can not be resolved in this study, it seems clear that the depositional ages of the Sindong Group and Wakino Subgroup seem different. Thus, further study is needed to interpret the depositional linkage between these two sedimentary units.

The newly assigned depositional age of the Sindong Group can also constrain the depositional age of the overlying Hayang Group. Based on palynological data (Choi 1985; Seo 1985; Choi 1987, 1989; Choi & Park 1987), the Hayang Group was interpreted to have been deposited during the Aptian and Albian. However, the depositional age of the Hayang Group should be equal to or younger than late Albian. In the Hayang Group, the Gusandong Tuff, which occurs in the upper

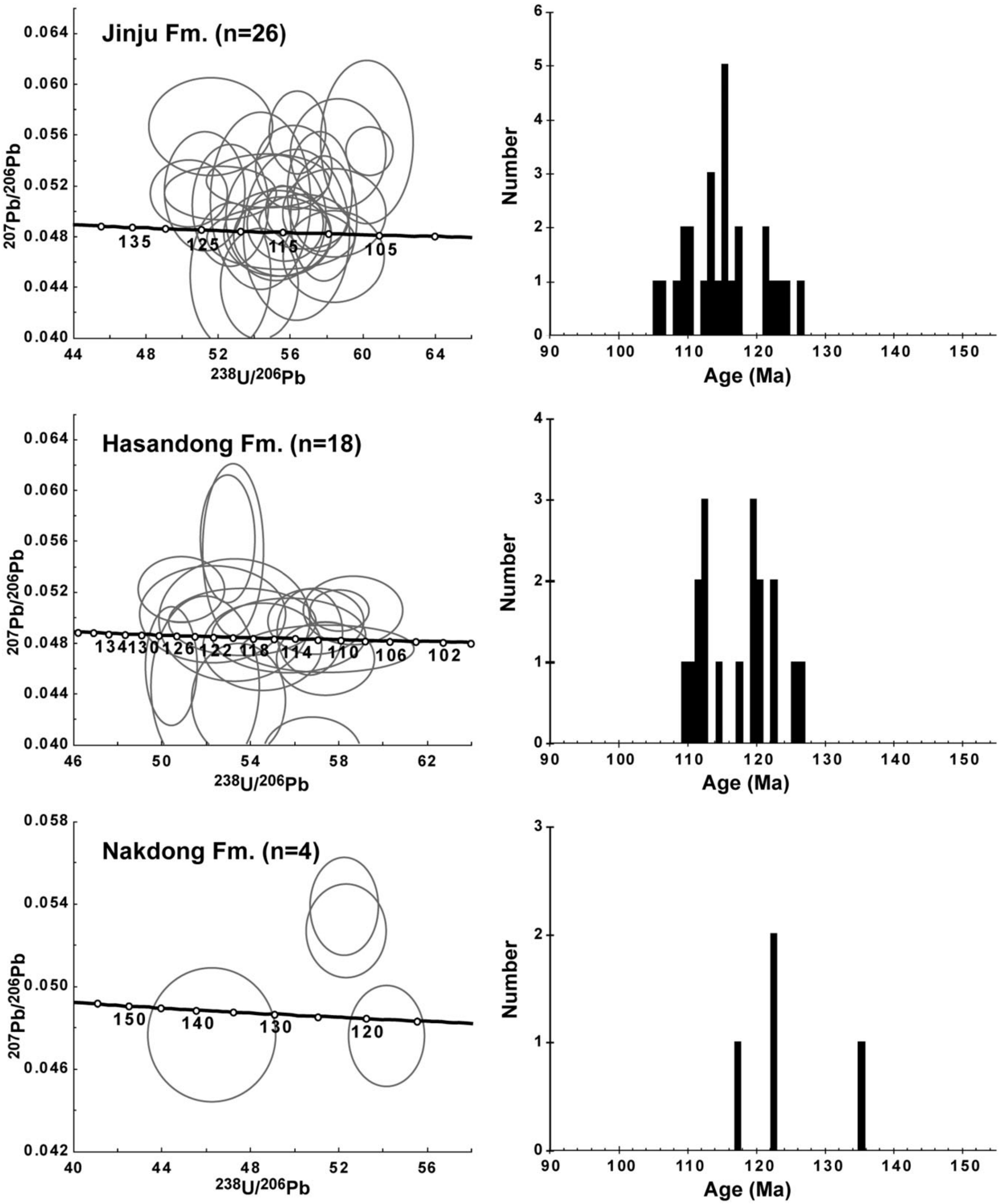

Fig. 3 U/Pb Terra–Wasserburg diagrams and histograms of U–Pb ages for detrital zircons from the Sindong Group. Error ellipses are at the 2σ level.

part of it, has been dated to be 97–96 Ma based on LA-ICP-MS U–Pb zircon dating (Jwa *et al.* 2009). In addition, the boundary between the Hayang Group and the overlying Yucheon Group has been suggested to be 81–80 Ma (Park *et al.* 2008). Considering these time frames, the Hayang Group is interpreted to have been deposited during the Cenomanian to early Campanian.

LOWER CRETACEOUS MAGMATIC ACTIVITY

The Sindong Group contains noticeable amounts of detrital magmatic zircons of Cretaceous age. The ages of Cretaceous detrital zircons in the Sindong Group indicate that magmatic activity occurred continuously in the source areas from 138 Ma to 106 Ma.

Paleocurrent data indicate sediment derivation from west and northwest (Chang & Kim 1968; Koh 1986), most probably from the Yeongnam Massif. However, there exists no report on the presence of Cretaceous igneous rocks in the Yeongnam Massif. The youngest granite in the Yeongnam Massif is 169 Ma (Sagong *et al.* 2005). Recently, Jwa *et al.* (2008) reported Cretaceous granitic rocks in the central Yeongnam Massif. They reported that there are two age groups of Cretaceous granitic rocks: 99–102 Ma and 82–83 Ma. These two groups of Cretaceous granitic rocks are younger than the Cretaceous igneous rocks for the Sindong Group in this study. Thus, this study reports the first Lower Cretaceous magmatic activity in the Yeongnam Massif and further in the southern Korean Peninsula. The lack of reports on the presence of Lower Cretaceous igneous rocks in the Yeongnam Massif suggests that the igneous rocks responsible for Cretaceous detrital zircons in the Sindong Group have been likely exhumed.

The spatial distribution of Lower Cretaceous magmatic activity can be inferred from the distribution of Cretaceous detrital zircons in the Sindong Group (Fig. 4). During deposition of the lowermost Nakdong Formation, episodic magmatic activity occurred in the Yeongnam Massif west of the Gunwi and Goryeong areas. With time, the locus of magmatic activity has migrated from northeast to southwest. During deposition of the Hasandong Formation, magmatic activity occurred continuously in the source area west of the Goryeong area, and new magmatic activity occurred in the southwestern Yeongnam Massif west of the Jinju area. However, during deposition of the Jinju Formation, there was magmatic activity all over the Yeongnam Massif, but it was more frequent in the southwestern and middle Yeongnam Massif with sporadic youngest magmatic activity in the northeastern Yeongnam Massif.

Sagong *et al.* (2005) reported an approximately 50-m.y. gap from the Late Jurassic to Early Cretaceous in granitoid ages in South Korea. A similar magmatic gap between 121 and 161 Ma has been also found in Japan (Sagong *et al.* 2005). They interpreted that abundant granitoid intrusions in South Korea were associated with the slow (~5–13 cm/yr) orthogonal subduction of the Izanagi Plate in the Middle Jurassic and the Late Cretaceous, whereas the magmatic quiescence appears to be related to shallow-angle subduction induced by fast convergence rate (~20–30 cm/yr) and possible subduction of an oceanic plateau in the Late Jurassic to Early Cretaceous. If we combine our Cretaceous magmatic ages derived from the Sindong Group with Sagong *et al.*'s (2005) data, the magmatic gap in South Korea becomes 20 m.y. from 158 Ma to 138 Ma, which is narrower than that suggested by Sagong *et al.* (2005). This narrow magmatic gap suggests that resumption of magmatic activities began earlier in the middle Early Cretaceous even during the oblique convergence period than in the commonly believed Late Cretaceous.

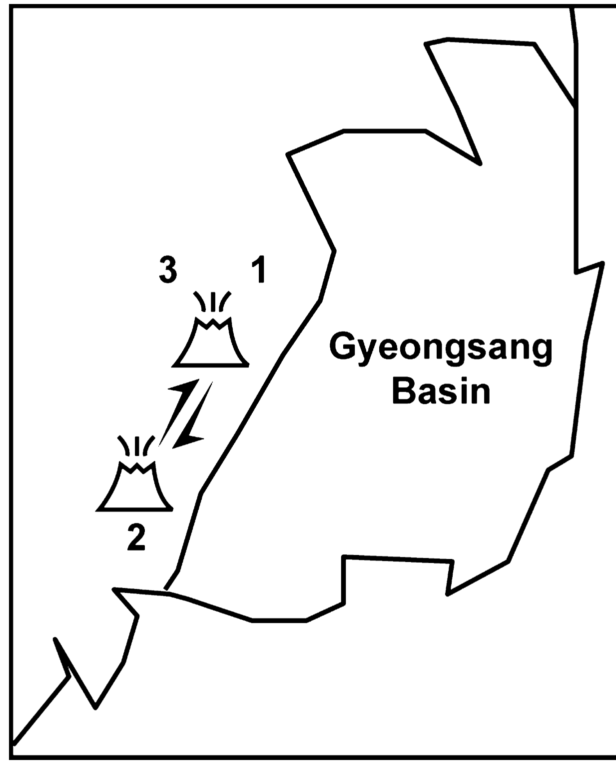

Fig. 4 Spatial distribution of Lower Cretaceous igneous activity in the Yeongnam Massif during deposition of the Sindong Group in the Gyeongsang Basin.

CONCLUSIONS

U–Pb geochronological analyses of detrital zircon grains from the Sindong Group, Gyeongsang Basin, southeastern Korea yield 48 Lower Cretaceous magmatic ages extending from 138 to 106 Ma. The youngest detrital zircon ages are 118 Ma for the Nakdong Formation, 109 Ma for the Hasandong Formation, and 106 Ma for the Jinju Formation, each representing the maximum depositional age of the corresponding formation in the Gyeongsang Basin. Accordingly, the Sindong Group was deposited during the late Aptian to late Albian, which is younger than previously thought. Cretaceous magmatic activity responsible for detrital zircons in the Sindong Group took place in different source regions in time and space. During deposition of the lowermost Nakdong Formation magmatic activity occurred in the northern and middle parts of the Yeongnam Massif. Then, it occurred dominantly in the middle and southern parts of Yeongnam Massif during deposition of the overlying Hasandong and Jinju Formations. The present study reports first the Lower Cretaceous magmatic activity in Korea as well as in East Asia, resulting in a narrower magmatic gap of about 20 m.y. than previously known.

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