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ORIGINAL PAPER

Sediment grain size does matter: implications of spatiotemporal variations in detrital zircon provenance for early Paleozoic peri-Gondwana reconstructions

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Abstract
A comprehensive understanding of the relationship between the Sino-Korean Craton (SKC) and the Gondwana supercontinent is crucial for accurate reconstruction of the tectonic evolution and early Paleozoic paleogeography of East Asia. To explore the link between the SKC and peri-Gondwana, we provide new detrital zircon U–Pb age data from litho- and bio-stratigraphically constrained lower Cambrian to Lower Ordovician sandstone deposits from the eastern margin of the SKC (Taebaeksan Basin). Results indicate that the two distinct age spectra of detrital zircon resulted from provenance change combined with a strong function of sediment grain size within host siliciclastic rocks of the Taebaek Group. The age spectra from coarse-grained sandstones display Paleoproterozoic (1.9 Ga) and Neoarchean (~ 2.5 Ga) peaks, indicating that the sediments were supplied from the basement rocks of the SKC. Conversely, age spectra from fine-grained siliciclastics contain late Mesoproterozoic (~ 1.0 Ga) and Neoproterozoic (~ 0.6 Ga) peaks, with or without a Paleoproterozoic signal, consistent with a Gondwanan sediment origin. These different age populations have been documented in multiple Cambrian and Ordovician sequences of the SKC and are consistently well correlated with sediment grain size. Coarse-grained sediments, sourced primarily from local basement rocks, were deposited in coastal, nearshore, and shelf environments, whereas fine-grained sediments were derived from more distal sources (i.e., the Gondwana mainland and/or the Gyeonggi Marginal Belt) and deposited in inner to outer shelf settings. Therefore, the repeated occurrence of sediment with two distinct provenances in the Cambrian–Ordovician siliciclastics of the SKC is likely a result of provenance shift integrated with changing depositional environments in an epeiric platform. This yielded variations in sediment grain size and source rock provenance, with and/or without a tectonic activity. Consequently, our results indicate that the SKC was adjacent to Gondwana during the early Paleozoic.

Keywords Sino-Korean Craton · Gondwana · Detrital zircon · Provenance · Paleogeography

Introduction

Detrital zircon geochronology has developed in the technology and knowledge rapidly over the past two decades and can be used to elucidate a wide range of geological processes. U–Pb ages of detrital zircons within siliciclastic sedimentary rocks can constrain maximum depositional ages, provenance, and stratigraphic correlations, in addition to refining paleogeographic reconstructions and the transcontinental dispersal pathways of ancient continents (Dickinson et al. 2012; Ingersoll et al. 2013; Niemi 2013; Gehrels 2014). The provenance of sedimentary rocks varies with depositional setting and sedimentary processes (Johnsson 1993). Thus, it is necessary to understand how sediments were transported and deposited to extract meaningful paleogeographic information from detrital zircons, particularly

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as the zircon population is also controlled by hydrodynamic fractionation of grain size in the host sediment (Bussient et al. 2011; Lawrence et al. 2011; Shaw et al. 2014; Zimmermann et al. 2015). Provenance analysis and determination of dispersal paths, therefore, depend on appropriate zircon data combined with a reliable stratigraphic, tectonic, and paleogeographic framework.

The early Paleozoic locations of the main tectonic blocks of Gondwana (i.e., Africa, Antarctica, Australia, India, and South America) are well established, based on paleobiogeography, paleomagnetic data, and stratigraphy, combined with detrital zircon geochronology (Fig. 1; e.g., Squire et al. 2006; Cawood et al. 2007; Flowerdew et al. 2007; Duan et al. 2012; Burrett et al. 2014; Li et al. 2017). However, the nature of the amalgamation and break-up of early Paleozoic continental/micro-continental blocks around Gondwana remains unclear. In particular, numerous tectonic models have been proposed for the paleogeography of the Sino-Korean Craton (SKC) relative to Gondwana (Fig. 1). Some models suggest that the SKC had a direct Gondwanan affiliation (e.g., Veevers 2004; Metcalfe 2006; McKenzie et al. 2011; Cho et al. 2014), whereas others indicate that the SKC was not connected to the margin of Gondwana (e.g., Li and Powell 2001; Cocks and Torsvik 2013; Burrett et al. 2014; Li et al. 2017). As both end-member models are supported by detrital zircon ages, the actual paleogeographic location of the SKC and its interaction with Gondwana during the early Paleozoic remain unclear.

In this study, we present new U–Pb detrital zircon ages acquired from an early Paleozoic succession in the Taebaeksan Basin, located on the eastern margin of the SKC. Age spectra and provenance of detrital zircon are assessed in the

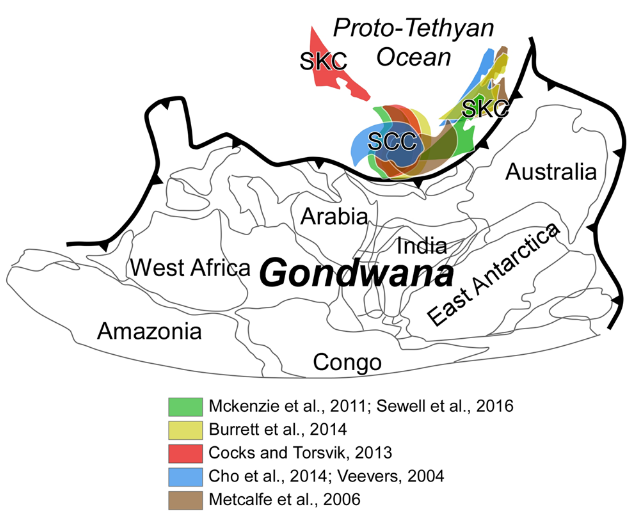


Fig. 1 Previous tectonic models for positions of the Sino–Korean and South China Cratons relative to the Gondwana supercontinent on Early Paleozoic (pre 460 Ma) geography in East Asia (modified from Li et al. 2017)

context of depositional environments established in previous studies (Kwon et al. 2006; Chough 2013). The aims of this study provide new insight into the interpretation of age distributions of detrital zircons for paleogeographic reconstruction based on relationship between sediment grain size and detrital zircon age spectra, which may be directly applicable to age data of early Paleozoic peri-Gondwana terranes.

Geological background

Regional geology

The Korean Peninsula contains distinct tectonostratigraphic terranes comprising three Precambrian massifs and two Paleozoic fold-and-thrust belts. The two belts are the Imjingang Belt, located between the Nangrim and Gyeonggi massifs, and the Okcheon Belt, between the Gyeonggi and Yeongnam massifs (Fig. 2). The Okcheon Belt consists of two deformed and metamorphosed sedimentary basins: the Okcheon Basin in the southwest and the Taebaeksan Basin in the northeast (Fig. 2b). Faunal province and lithological correlations indicate that the Okcheon and Taebaeksan basins were once part of the South China Craton (SCC) and the SKC, respectively (Chough 2013; Ree et al. 2001; McKenzie et al. 2011) and that they subsequently merged with one another along the South Korea Tectonic Line (SKTL; Fig. 2). Recently, Cho et al. (2017a, b) proposed a new tectonic framework of the Korean Peninsula, placing supra-crustal rocks of the Gyeonggi Marginal Belt (GMB) on the Gyeonggi Massif. The GMB consists of three sub-belts, the Imjingang Belt in the north, the Taean-Hongseong Complex in the west, and some units of the Okcheon Basin in the south (Fig. 2b). Cho et al. (2017a, b) suggested that the GMB occurred as a fold-and-thrust belt initiated in an arc-related tectonic regime around 850–750 Ma, then experienced crustal thickening collisional orogeny and extensional magmatism during the late Paleozoic and early Mesozoic, respectively. The GMB is characterized by a tectonic mixture of Mesoproterozoic to Lower Permian supra-crustal rocks of the SCC-like affinity, built on a SKC-like basement (Cho et al. 2017a, b).

The Taebaeksan Basin consists mainly of the lower Paleozoic Joseon Supergroup and the upper Paleozoic Pyeongan Supergroup (Fig. 2c). The Joseon Supergroup consists of mixed carbonate and siliciclastic rocks that unconformably overlie Mesoproterozoic–Paleoproterozoic basement rocks. The Joseon Supergroup is divided into five lithologic units according to their regional occurrence: the Taebaek, Yeongwol, Yongtan, Pyeongchang, and Mungyeong groups. Based on the integrated interpretation of geochemical and detrital zircon data, Kim et al. (2013) suggested that the western Taebaeksan Basin (the Yeongwol Group) was situated at the southern margin of the SKC as part of the Gondwana

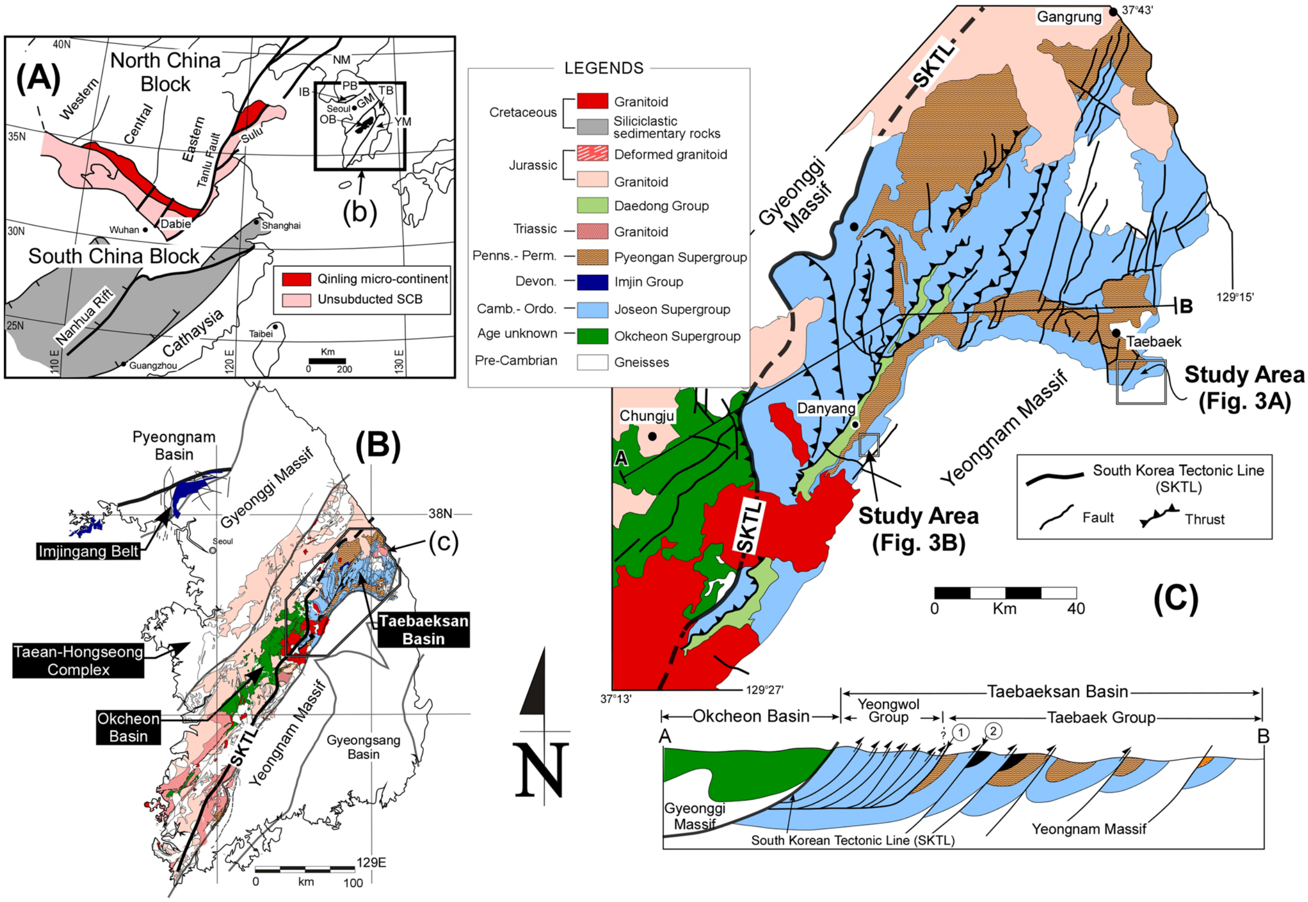


Fig. 2 **a** Simplified tectonic framework in the northeast Asian margin (modified from Zhao et al. 2005; Xia et al. 2009). **b** Schematic tectonic map showing major sedimentary basins, orogenic belts, cratonic blocks (massif), and other geologic features in Southern Korean Peninsula. **c** Regional geological map and cross-section of the Taebaeksan basin and northeast Okcheon basin (modified from Chough 2013). *NM* Nangrim massif, *PB* Pyeongnam basin, *IB* Imjingang belt, *GM* Gyeonggi massif, *OB* Okcheon Basin, *TB* Taebaeksan Basin, *YM* Yeongnam massif, *SKTL* the South Korean Tectonic Line

margin, whereas the eastern Taebaeksan Basin (the Taebaek Group) was distal to the southern margin of the SKC during the Cambrian.

Detrital zircons have been acquired from several siliciclastic units of the Taebaek Group (Figs. 2c, 3). The Taebaek Group consists of 11 formations (total thickness of 1000–1400 m): the Jangsan, Myeonsan (lateral equivalent of the Jangsan Formation), Myobong, Daegi, Sesong, Hwajeol, Dongjeom, Dumugol, Makgol, Jigunsan, and Duwibong formations in ascending order (Fig. 3). The Precambrian basement rocks underlying the Taebaek Group consist of metasedimentary rocks of the Yulli Group (deposited between 2180 and 2010 Ma) and the Hongjesa granitic gneiss, which intrudes the Yulli Group at ca. 2000 Ma (Chough 2013).

The Jangsan, Myeonsan, and Dongjeom formations comprise mainly conglomerates and medium- to coarse-grained sandstones, and the Myobong, Sesong, and Jigunsan formations consist primarily of marine mudstones and shales (Fig. 3c). The remainder of the formations in the Taebaek Group are made up of shallow-marine carbonates to deeper-marine limestone–shale interbeds (Kwon et al. 2006). The fine- and coarse-grained siliciclastic rocks are interpreted to have formed in offshore and shoreface environments, respectively, whereas carbonates formed in ramp to peritidal environments (Chough 2013; Kim and Lee 2004; Kwon et al. 2006). Although detrital zircons from the siliciclastic-dominated formations (e.g., the Jangsan/Myeonsan, Myobong, Sesong, and Dongjeom formations) have been reported previously (McKenzie et al. 2011; Lee et al. 2012, 2016; Kim et al. 2013, 2017), this study presents the variations of detrital zircon age spectra from the lower to upper members of the Dongjeom Formation and additional results from the Jangsan and Myobong formations in the Danyang area.

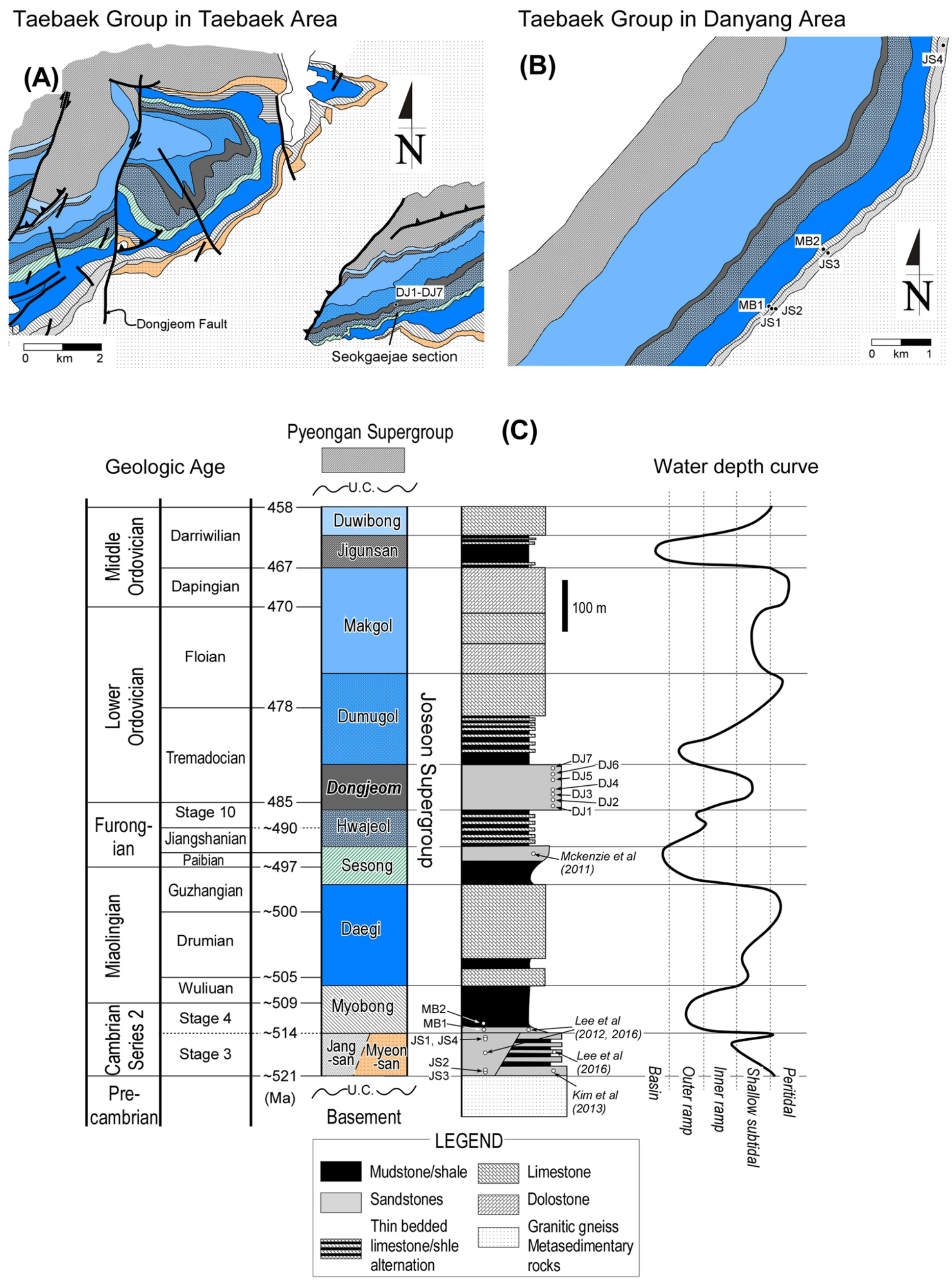


Fig. 3 **a**, **b** Geological map of the Taebaek Group in the southeastern margin of the Taebaeksan Basin (see Fig. 2c) with sampling sites. **c** Lithostratigraphic nomenclatures and major lithologies of the Cambrian–Ordovician Joseon Supergroup in the basin (modified from Kwon et al. 2006). Stratigraphic columns with water depth curve are modified from Kwon et al. (2006). Sampling locations for analysis are also shown

Previous studies on the depositional environments of siliciclastic rocks of the Joseon Supergroup

The Jangsan and Myeonsan formations consist of massive sandstones, cross-stratified or horizontally stratified sandstones, disorganized conglomerates, and foreset-bedded sandstones (Kwon et al. 2006). Sedimentological analysis indicates that the Jangsan Formation was deposited in a shallow-marine environment (from the shoreface to inner shelf), whereas the Myeonsan Formation was formed in a tidally influenced restricted embayment (Chough 2013). Although the Jangsan and Myeonsan formations are generally devoid of fossils, the occurrence of the trace fossils *Skolithos* and *Laevicyclus* in the Myeonsan Formation suggests a post-Precambrian age. The siliciclastic facies of the Myobong Formation comprises homogeneous laminated mudstone, laminated and massive sandstone, and normally graded sandstone, which were deposited in a hemi-pelagic setting in an outer-shelf environment, below the storm wave base (Kwon et al. 2006). Four Cambrian trilobite biozones (Chough 2013) the *Redlichia*, *Elrathia*, *Mapania*, and *Bailiella* zones) have been identified within the Myobong Formation (Choi and Chough 2005), which suggests a depositional age from the informal Stage 4 of Cambrian Series

2 to the Wuliuan Stage of the Miaolingian Series (Chough 2013). Collectively, these siliciclastic facies represent initial inundation and subsequent deepening during the late early Cambrian to middle Miaolingian (Fig. 3c; Kwon et al. 2006).

The Sesong Formation (Fig. 3c) is dominated by gray homogeneous or laminated mudstone, massive or laminated sandstone, and limestone pebble conglomerate (Kwon et al. 2006). The mudstone and sandstone facies likely formed in a hemi-pelagic setting in an outer-shelf environment and in a proximal environment affected by storm currents, respectively. Trilobite biozones containing *Jiulongshania*, *Neodrepanura*, *Liostracina smesi* (Guzhangian), *Fenghuangella laevis*, *Prochuangia mansuyi*, *Chuangia* (Paibian), and *Kaolishania* (Jiangshanian) have been identified within the Sesong Formation (Park et al. 2013; Park and Choi 2012).

The Dongjeom Formation is informally divided into three members, consisting of five subfacies associations (subFA1 to subFA5; Kwon et al. 2006). The lower member (subFA1) comprises mainly sandstone–shale couplets and dark gray mudstone. The middle member (subFA2) consists of massive, laminated, and cross-stratified sandstones. The upper member (subFA3–5) is characterized by alternating massive sandstones and siltstones (subFA3), which grade upward into calcareous and nodular shales, limestone–shale couplets, and grainstone (subFA4), overlain by massive and crossed-stratified sandstone (subFA5; Kim and Lee 2004; Kwon et al. 2006). Kwon et al. (2006) suggested that the lower member (subFA1) and middle member (subFA2) represent offshore and shoreface environments, respectively, whereas the upper member records alternating offshore and shelf conditions (subFA3), overlain by carbonate ramp (subFA4) and clastic shoreface (subFA5) deposits. Trilobite biozones containing the *Eosaukia*, *Pseudokolinioidea*, and *Richardsonella* fauna are recognized in the lower member of the Dongjeom Formation (Lee and Choi 2011), and the Cambrian–Ordovician boundary lies within the *Richardsonella* Zone (Lee and Choi 2011). The absence of fossiliferous material means that the upper limit of the depositional age of the Dongjeom Formation is uncertain. However, the occurrence of the *Asaphellus* Zone (upper Tremadocian; Lower Ordovician) in the lower part of overlying Dumugol Formation indicates that deposition of the Dongjeom sandstone continued until the middle Tremadocian.

Sampling and analytical methods

Petrographic analysis of samples from the Dongjeom Formation in the Taebaek Group was carried out using a traditional point-counting method, and estimated framework grain proportions are summarized in Table 1. Seven sandstone samples (DJ1–DJ7) were collected from the base to the top of the Dongjeom Formation in the Seokgaejae section, where the formation is ~ 93 m thick (Fig. 3a, c). In addition, four samples of sandstone from the Jangsan Formation (JS1–JS4) and two samples of sandstone from the Myobong Formation (MB1 and MB2) were collected from the Taebaek Group in the Danyang area (Fig. 3b, c) to assess lateral variations (Fig. 3).

Zircon grains were mechanically isolated using conventional mineral separation techniques that employed crushing, grinding, and sieving, followed by handpicking of individual

Table 1 Modal analyses and summary of petrographic observations of medium- and coarse-grained sandstones from the Dongjeom Formation

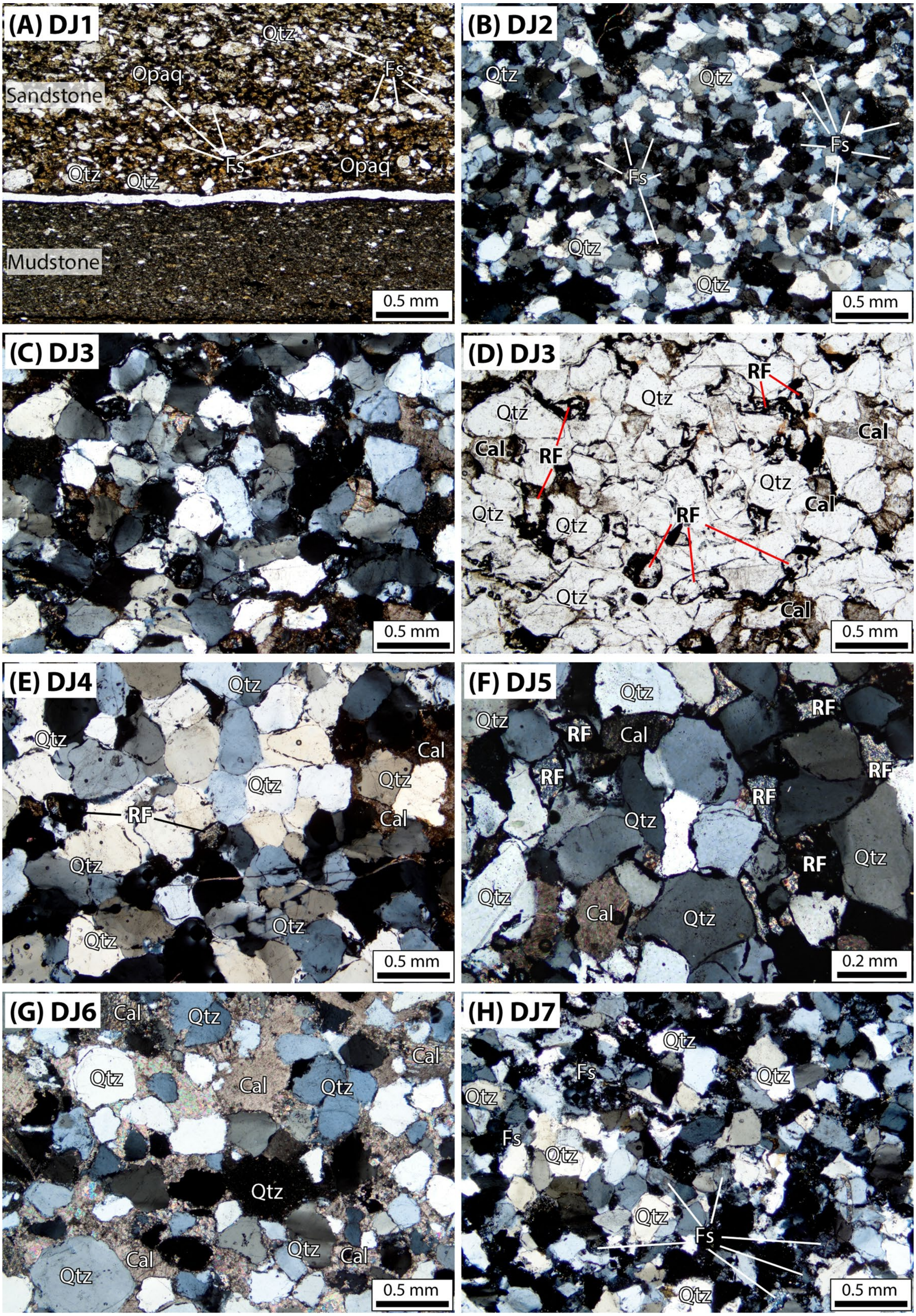
Sample #	DJ2	DJ3	DJ4	DJ5	DJ6	DJ7
Quartz	61.2	39.6	42.6	33.8	42.4	37.0
Feldspar	18.8	8.6	2.0	7.4	1.2	34.2
RF[a]	10.0	18.8	6.2	21.4	1.4	2.2
Cements						
Calcite	0.0	15.0	6.4	8.0	52.0	0.4
Quartz	4.6	7.0	28.2	17.8	1.0	14.2
Opaque	5.4	11.0	14.6	11.6	2.0	12.0
Grain size[b]	Fine-medium sand	Medium-coarse sand	Medium-coarse sand	Fine-medium sand	Medium-coarse sand	Fine- medium sand
Rock type	Lithic arkose	Feldspathic litharenite	Sublitharenite	Feldspathic litharenite	Quartz arenite	Arkose
Facies[c]	Shoreface (subFA2)			Shelf (subFA3)		Shoreface to offshore transition (subFA5)

Total 500 points are counted in each sample

[a]Rock fragments (RF) in the samples DJ2, DJ3, DJ4, and DJ5 are metamorphic rocks (slate/phyllite clasts)

[b]Grain size after Wentworth classification

[c]Sedimentary facies association from Kwon et al. (2006)


(A) DJ1
Qtz
Opaq
Sandstone
Fs
Fs
Qtz
Qtz
Opaq
Mudstone
0.5 mm
(B) DJ2
Qtz
Qtz
Fs
Fs
Qtz
Qtz
0.5 mm
(C) DJ3
0.5 mm
(D) DJ3
RF
Qtz
Qtz
Cal
RF
Cal
Qtz
Cal
Qtz
Qtz
RF
Qtz
Cal
0.5 mm
(E) DJ4
Qtz
Qtz
Cal
Qtz
Qtz
RF
Cal
Qtz
Qtz
Qtz
0.5 mm
(F) DJ5
Qtz
Qtz
RF
Cal
RF
RF
RF
RF
Qtz
RF
Qtz
Qtz
Cal
Qtz
0.2 mm
(G) DJ6
Cal
Qtz
Cal
Qtz
Cal
Qtz
Qtz
Qtz
Cal
Qtz
Cal
Qtz
0.5 mm
(H) DJ7
Qtz
Fs
Qtz
Qtz
Fs
Qtz
Qtz
Fs
Qtz
0.5 mm

◂**Fig. 4** Photomicrographs of sandstones in the Dongjeom Formation, Taebaek Group. **a** Sample DJ1. **b**–**h** Fine- to coarse-grained sandstones of samples DJ2–DJ7. All photos are taken under crossed polarized light except for **d**. Mineral abbreviations, *Qtz* quartz, *Fs* feldspar, *RF* rock fragments, *Opaq* opaque mineral, *Cal* calcite

zircons under a binocular microscope. A total of 1000 zircon grains obtained from the three formations were mounted on epoxy resin. The internal structure of the grains was assessed using both transmitted- and reflected-light microscopy, and scanning electron microscope-cathodoluminescence (CL) imaging. U–Pb isotopic analyses of detrital zircon grains were conducted by laser ablation–multicollector–inductively coupled plasma–mass spectrometer (LA–MC–ICP–MS; Nu Plasma II/NWR193^{UC}) and sensitive high-resolution ion microprobe (SHRIMP; IIe/MC) at the Korea Basic Science Institute, Ochang, Korea. Calibration of inter-element fractionation was performed using the standard zircon 91500 (age 1065 Ma; Wiedenbeck et al. 1995). The zircon Plešovice was employed as the external standard, with a recommended weighted mean $^{206}Pb/^{238}U$ age of 337.1 Ma (Sláma et al. 2008), in addition to zircon standards SL13 and FC1. Reduction of raw data and final age calculations were made using the SQUID and Isoplot/Ex add-ins for Microsoft Excel, and IsoplotR (Vermeesch 2018). U–Pb detrital zircon data are listed in Supplementary Tables S1–S3. Analyses with discordance less than 15% were selected for relative probability plots. $^{207}Pb/^{206}Pb$ ages are used when the age exceeds 1000 Ma, with $^{206}Pb/^{238}U$ ages quoted otherwise. Data of reference zircon also are summarized in Supplementary Tables S4 and Figure S1.

Petrography

Samples from the Dongjeom Formation within the Taebaek Group consist mainly of fine- to coarse-grained sandstone (Fig. 4). Sample DJ1, from the lowermost subFA1, contains both fine-grained sandstone and dark gray mudstone (Fig. 4a). Samples DJ2 (fine- to medium-grained sandstone) and DJ3 and DJ4 (medium- to coarse-grained sandstone) make up subFA2. Samples DJ5 (fine- to medium-grained sandstone) and DJ6 (medium- to coarse-grained sandstone) are massive sandstone (from subFA3) and crudely stratified calcareous sandstone (from subFA3), respectively. Sample DJ7 (fine- to medium-grained sandstone) is from a cross-stratified sandstone unit in subFA5. The Jangsan sandstone (samples JS1–4) is a coarse- to very coarse-grained quartzose sandstone, and samples MB1 and MB2 of the Myobong sandstone comprise dark gray siltstone and fine-grained mica-rich sandstone, respectively (Fig. 5).

Samples from the Dongjeom Formation contain a range of framework grain proportions and cement compositions. Modal proportions of quartz and feldspar range from 34 to 61% and from 1 to 34%, respectively, whereas metamorphic rock fragments (mostly slate and phyllite clasts) range from 1 to 21% (Table 1; Fig. 4). Most grains are subangular–subrounded (Fig. 4). Hematite cement commonly rims detrital framework grains and makes up 2–15% of the rock volume. Calcite and quartz commonly occur as cement around grains (Table 1; Fig. 4b–f). Sample DJ6 contains quartz grains (~ 0.5 mm diameter) in calcite cement that makes up 52% of the rock volume (Fig. 4g), interpreted to be the result of feldspar dissolution and subsequent calcite cementation within secondary pores. Sample DJ7 (uppermost Dongjeom Formation) consists of 37% quartz and 34% feldspar (Fig. 4h). Sandstones from the top of the Jangsan Formation (collected in the Danyang area) comprise mainly quartz and minor muscovite (Fig. 5a, b). Coarse-grained quartz in these samples shows undulose extinction and subgrain boundaries, reflecting dynamic recrystallization. The Myobong samples consist mainly of quartz, muscovite, chlorite, and opaque minerals (Fig. 5c, d). Quartz is fine-grained and is aligned with mica along a crenulation cleavage.

Samples DJ3 and DJ5 are feldspathic litharenites, and samples DJ2 and DJ7 are lithic arkose and arkose, respectively. Based on Gilbert's classification scheme, samples DJ4 and DJ6 are sublitharenite and quartz arenite (Table 1), respectively. In the provenance discrimination diagram of Dickinson et al. (1983), samples DJ2–DJ6 plot within the recycled orogen field and sample DJ7 plots in the basement uplift field (Fig. 6).

U–Pb detrital zircon ages

Jangsan and Myeonsan formations

Zircon grains from samples JS1–JS4 are subrounded with a grain size of 100–150 μm and show oscillatory and banded internal zoning with or without an inherited core. In total, 178 of 222 zircon spot analyses yielded concordant ages and relatively high Th/U ratios (Fig. 7a, b). The concordant ages of the Jangsan Formation can be classified into two subgroups (Fig. 7b): (1) middle Paleoproterozoic (2200–1800 Ma) with peaks at ~ 1900 Ma and ~ 2200 Ma; and (2) early Paleoproterozoic-Neoarchean (2800–2400 Ma) with a peak at ~ 2500 Ma. These age populations are almost identical to those of the Jangsan Formation in the Taebaek area (Lee et al. 2012).

Detrital zircon U–Pb ages of coarse-grained sandstone from the Myeonsan Formation were reported by Lee et al. (2012), Kim et al. (2013), and Jang et al. (2018), and can be classified into three groups of zircon age spectra (Figs. 8, 9): (1) late Paleoproterozoic (2000–1800 Ma); (2) middle Paleoproterozoic (2300–2000 Ma); and (3) early Paleoproterozoic–Neoarchean (2800–2400 Ma). The youngest

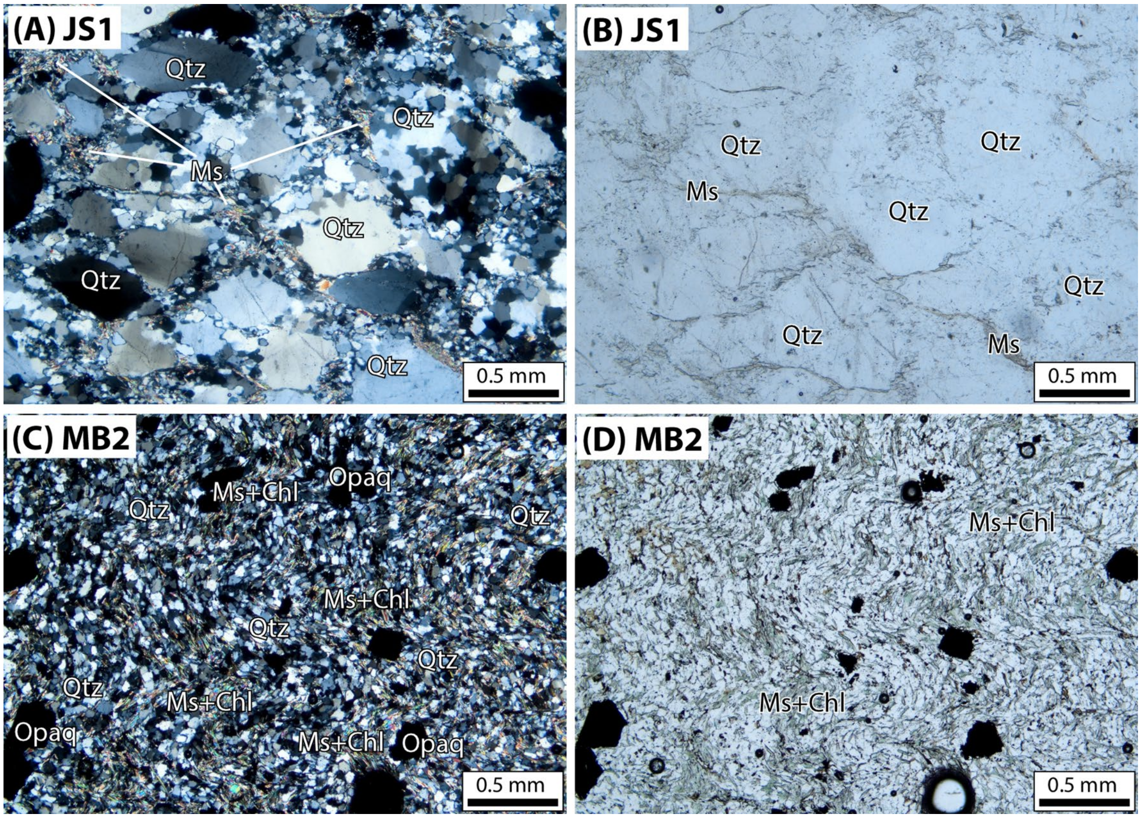


Fig. 5 Photomicrographs of sandstones in the Jangsan and Myobong formations, Taebaek Group in Danyang area. **a**, **b** Jangsan Formation. **c**, **d** Myobong Formation. Mineral abbreviations, *Qtz* quartz, *Opaq* opaque mineral, *Ms* muscovite, *Chl* chlorite

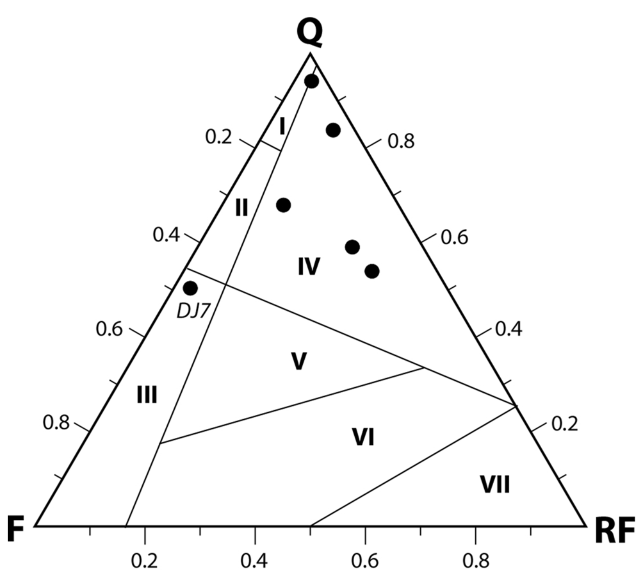


Fig. 6 Q (quartz)–F (feldspar)–RF (rock fragment) diagram for framework grains from sandstones in the Dongjeom Formation. Provenance fields are from Dickinson et al. (1983): I: stable craton, II: Transitional continental, III: Basement uplift, IV: Recycled orogen, V: Dissected arc, VI: Transitional arc, VII: Undissected arc

U–Pb detrital zircon age in the Myeonsan Formation is ca. 510–500 Ma.

Myobong Formation

Detrital zircon grains from MB1 and MB2 are subrounded with grain sizes of 40–100 µm. Most grains show oscillatory growth zoning and relatively high Th/U ratios (Fig. 7c, d), consistent with a magmatic origin. In total, 65 of 77 U–Pb spot analyses are concordant (Fig. 7d). The spectra of concordant U–Pb ages of the Myobong Formation are markedly different from those of the Jangsan and Myeonsan formations and can be classified into three subgroups: (1) Neoproterozoic–late Mesoproterozoic (1200–700 Ma) with a peak at ~ 1000 Ma; (2) late Mesoproterozoic–Paleoproterozoic (2200–1500 Ma); and (3) early Paleoproterozoic–Neoarchean (2800–2400 Ma) with a peak at ~ 2500 Ma (Fig. 7d). The average age of younger Paleozoic zircons is 508 Ma.

The Myobong Formation in the Taebaek area (Lee et al. 2012, 2016) is dominated by Neoproterozoic detrital zircon ages between 770 and 550 Ma, with a prominent peak at ~ 600 Ma (Figs. 8, 9). A secondary cluster occurs between 1030 and 820 Ma, with a peak at ~ 1000 Ma. Moreover, there

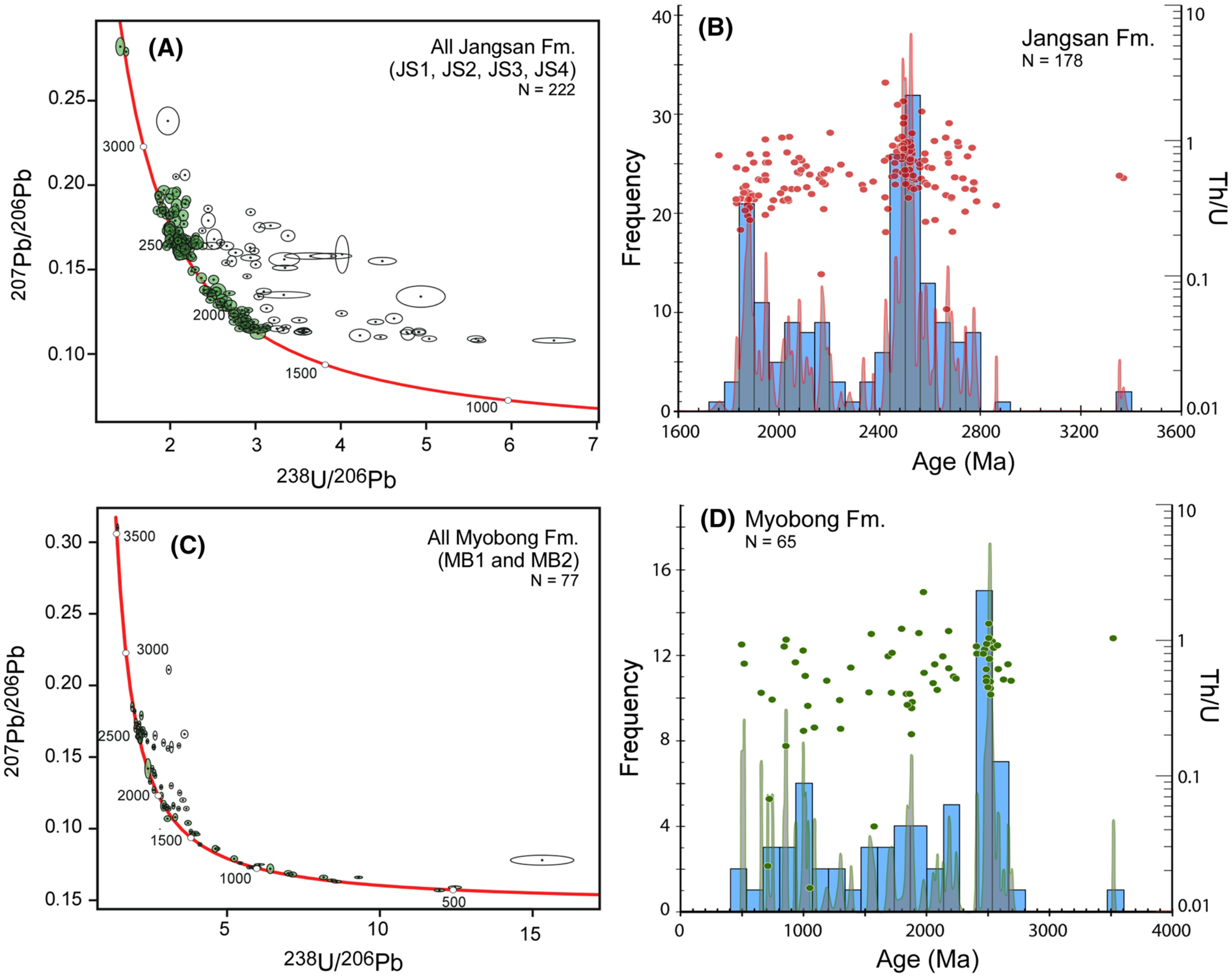


Fig. 7 Terra–Wasserburg and probability diagrams with Th/U ratios of U–Pb detrital zircon ages of sandstones collected from Danyang area. **a**, **b** The Jangsan Formation. **c**, **d** The Myobong Formation

is a notable cluster at 1900–1080 Ma, and minor peaks at 1500 Ma and 1800 Ma.

Sesong Formation

Detrital zircon U–Pb ages of fine-grained sandstone from the Sesong Formation in the Taebaek area were reported by McKenzie et al. (2011), who analyzed detrital zircons from the *Kaolishania* Zone, collected from the upper part of the Sesong Formation where laminated, homogeneous, or normal-graded fine- to medium-grained sandstone is present (McKenzie et al. 2011). The resultant age spectrum contains broad Mesoproterozoic (1040–1000 Ma) and Paleoproterozoic (2300–1600 Ma) peaks, in addition to subordinate Neoproterozoic (~ 800 Ma) and Neoarchean (~ 2600 Ma) peaks (Figs. 8, 9; McKenzie et al. 2011). The three youngest concordant ages yield a weighted mean $^{206}Pb/^{238}U$ age of 483 Ma.

Dongjeom Formation

A total of 1700 zircon grains were separated from samples DJ1–DJ7. The zircons are mostly angular to subangular, and grain size increases from 20 to 100 μm in the lower part of the Dongjeom Formation to 40–200 μm in the upper part (Fig. 10). Most grains show banded and oscillatory growth zoning with a high Th/U ratio, suggesting a magmatic origin. Some grains are light to dark gray in CL and lack zoning (Fig. 10).

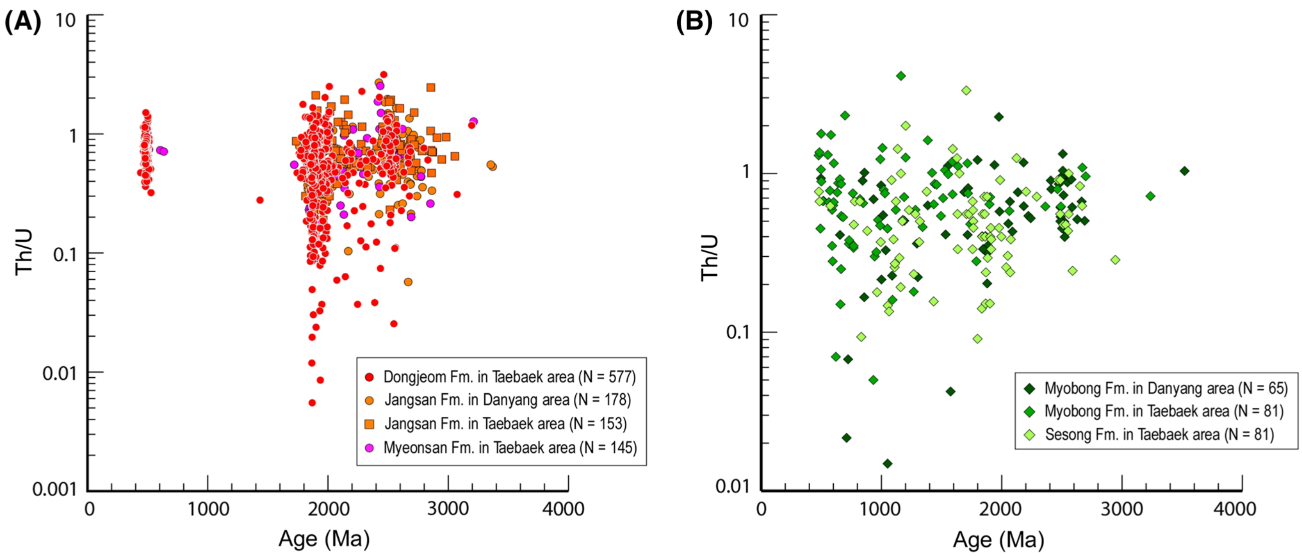


Fig. 8 Concordant age versus Th/U diagrams. **a** Detrital zircons in coarse-grained sandstones from the Myeonsan, Jangsan, Dongjeom formations in the Taebaek Group. **b** Fine-grained sandstones from the Myobong and Sesong formations. Data of the Jangsan, Myeonsan, Myobong, and Sesong formation in the Taebaek area are from McKenzie et al. (2011), Lee et al. (2012, 2016), and Kim et al. (2013)

There were no Neoproterozoic detrital zircons in the seven analyzed samples. Instead, the population contains prominent age peaks in the late Cambrian–Early Ordovician (~ 500 Ma) and Paleoproterozoic (~ 1900 Ma), as well as subordinate Neoarchean (2600–2500 Ma) peaks (Fig. 11). The proportion of younger ages varied from 33 to 38% in sample DJ1 (basal offshore) and DJ2–DJ4 (shoreface), to 10–15% in samples DJ5 and DJ6 (shelf), and sample DJ7 (shoreface to offshore transition; Table 1). The younger concordant ages give a weighted mean $^{206}Pb/^{238}U$ age of 500–480 Ma with relatively high Th/U ratios (0.3–2.0), indicating that these zircons formed as a result of early Paleozoic magmatic activity (Figs. 8, 11).

Interpretations and discussion

Origin of detrital zircons from the Dongjeom Formation in the Taebaeksan Basin

Detrital zircons from the Dongjeom Formation can be grouped into two populations: (1) Paleoproterozoic–Archean, and (2) late Cambrian to Early Ordovician, without the Neo- and Mesoproterozoic age populations (Fig. 11). Paleoproterozoic–Archean age peaks are characteristic of basement SKC rocks (Darby and Gehrels 2006; Kim et al. 2012) and are also well preserved in the Jangsan and Myeonsan formations (Lee et al. 2012, 2016; Kim et al. 2013; Jang et al. 2018; Fig. 9).

The late Stage 10 (Cambrian) to early Tremadocian depositional age of the Dongjeom Formation can be defined using trilobite faunal assemblages (Fig. 3; Lee and Choi 2011) and is consistent with detrital zircon ages (500–480 Ma; Fig. 11). As sediments of the Dongjeom Formation are interpreted to have originated in a recycled orogen and basement uplift (Fig. 6), these younger detrital zircon ages indicate relatively rapid rifting and erosion of the source. This rifting and erosion must have taken place after the magmatic event of the late Cambrian–Early Ordovician. Cambrian–Ordovician (520–470 Ma) magmatism/volcanism has also been documented in the North Quilian, Qinling, and Lhasa terranes, each of which was likely situated along the northeastern margin of Gondwana at the time (Fig. 1; Xu et al. 2005; Zhu et al. 2012; Li et al. 2017). The geochemistry of igneous rocks and detrital zircon indicates that this magmatic/volcanic activity occurred at an active continental margin (Zhu et al. 2012; Kim et al. 2013) and/or an oceanic ridge/rift (Xu et al. 2005; Cho et al. 2014). Ordovician volcanic activity recorded by the Mungyeong Group (on the southwestern margin of the Taebaeksan Basin) has been reported by Cho et al. (2014). The ca. 460 Ma volcanic rocks in this group originate from bimodal volcanism in a within-plate tectonic setting (e.g., a continental rift). Although tectonic and paleogeographic relationships between the Taebaek and Mungyeong groups are equivocal so far, we suppose that the younger detrital zircon grains of the Dongjeom Formation in the Taebaeksan Basin are probably derived from the upper Cambrian–Lower Ordovician volcanic rocks that formed around the margin of Gondwana (Choi 2018).

Consequently, the Paleoproterozoic and Neoarchean detrital zircons of the Dongjeom Formation were derived from the basement rocks of the SKC, whereas the late

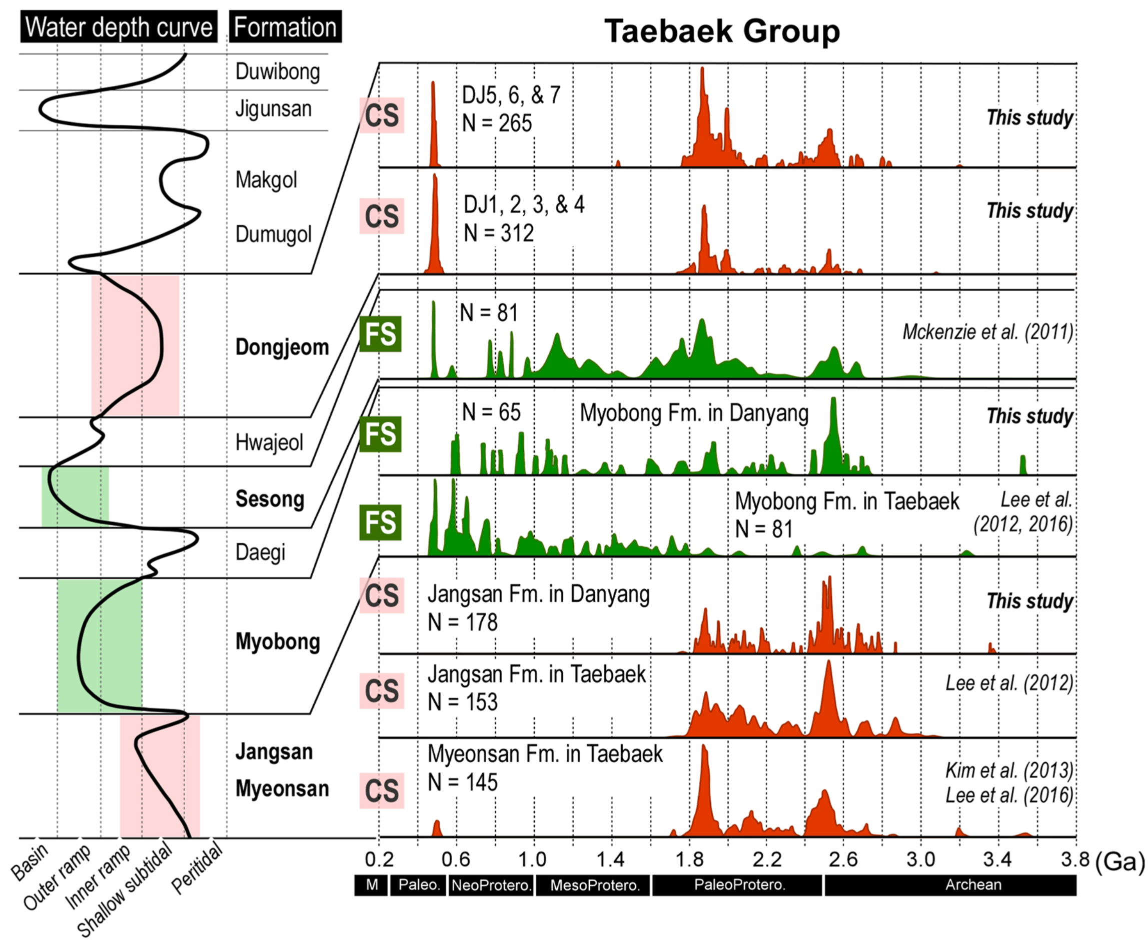


Fig. 9 Relative probability diagrams combined with depositional environments and water depth change (from Kwon et al. 2006). The concordant age distributions of detrital zircon are from the Cambrian and Ordovician siliciclastic sedimentary rocks of the Taebaek Group in the Taebaeksan Basin. *CS* medium- to very coarse-grained sandstone, *FS* siltstone to fine-grained sandstone

Cambrian–Early Ordovician detrital zircon grains were likely supplied and transported from a rift and/or magmatic arc that developed around the margin of Gondwana (Wang et al. 2010; Kim et al. 2013; Cho et al. 2014; Li et al. 2017; Choi 2018). Although the younger detrital zircon with and/or without Neo- and Mesoproterozoic age peaks in the Taebaeksan Basin was conventionally interpreted as a Gondwanan affinity (Cawood et al. 2007, 2013; Weislogel et al. 2010; Zhai and Santosh 2011; Chough 2013; Fig. 9), these age populations also have documented in the Pyeongnam Basin of the North Korea and the Shandong Peninsula of eastern China with the SKC affinity (Dong et al. 2013; Yang et al. 2016; Cho et al. 2017a, b).

Implications for two different age populations of detrital zircon in the Taebaeksan Basin

There are two distinct detrital zircon age fractions in siliciclastic rocks of the Taebaek Group: (1) Paleoproterozoic and Neoarchean populations (without Neo- and Mesoproterozoic peaks) within the lower Cambrian Jangsan and Myeonsan formations and the upper Cambrian–Lower Ordovician Dongjeom Formation (Fig. 9; with the exception of a 500–480 Ma peak in the Dongjeom Formation); and (2) Neo- and Mesoproterozoic populations with or without subordinate Paleoproterozoic ages in the Myobong and Sesong formations (Fig. 9). The former ages seem to be a distinct feature of the Yeongnam Massif with SKC affinity (Kim et al. 2012). The latter is similar to the age distribution recorded by Cambrian–Ordovician sedimentary rocks of the Gondwanan mainland (Fig. 12; Cawood and Nemchin 2000; Squire et al. 2006; Cawood et al. 2007, 2013; Flowerdew et al. 2007; Wang et al. 2010; Weislogel et al. 2010; McKenzie et al. 2011; Kim et al. 2013; Kim and Ree 2016), and a Neoproterozoic microcontinent occupied at the SKC margin (Dong et al. 2013; Yang et al. 2016; Cho et al. 2017a, b).

In attempting to understand provenance of the two distinct age populations in Taebaek Group of the Taebaeksan Basin,

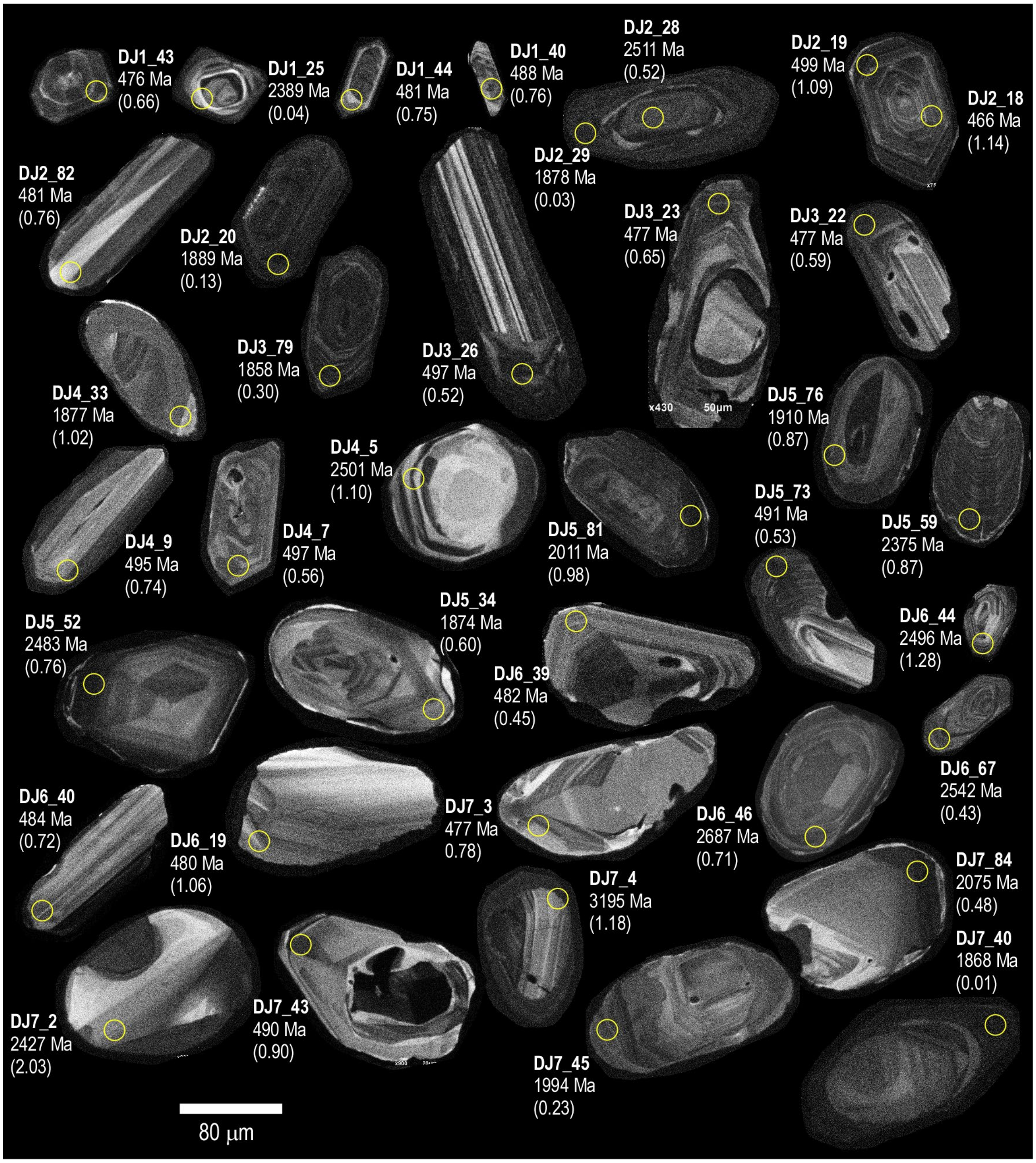


Fig. 10 Representative CL images for zircon grains from the sandstone samples (DJ1–DJ7) of the Dongjeom Formation. Each spot of the LA–MC–ICPMS analysis (circle) is shown together with the spot number and $^{206}Pb/^{238}U$ or $^{207}Pb/^{206}Pb$ ages. The number in the parenthesis represents value of Th/U

we envisage two possible scenarios. In the first scenario, we propose the Taebaek Group to have once been a part of the SKC with a separate microcontinent (i.e., GMB). The GMB, defined by Cho et al. (2017a, b), preserves the Mesoproterozoic rocks along with the later episodes of ca. 0.8–0.7 Ga arc formation or rifting, and ca. 0.4–0.5 Ga arc magmatism and metamorphism, then followed by a subsequent Triassic collision. Similar geochronological features associated with Gondwana affinity also are documented in the SKC interior (e.g., Penglai Group in Shandong Peninsula; Zhou et al. 2008). Notably, these events are also recorded in the SCC (Hacker et al. 1998, 2006; Bryant et al. 2004; Wang et al. 2004; Ratschbacher et al. 2006). Thus the GMB might have played an important role as potential provenance for the Myobong and Sesong formations if the GMB occupied around the southern margin of the SKC. However, two problems associated with this possibility are that (1) the absence of Meso- and Neoproterozoic signatures in the Dongjeom

Formation; and (2) repetition of two distinct age spectra during relatively short time interval (ca. 40 Myr).

The second possible scenario suggests that the Taebaek Group might once have been a part of SKC and was deposited near the Gondwana margin. On the basis of detrital zircon age populations and species-level polymerid trilobite biogeography, McKenzie et al. (2011) proposed that the southern margin of the SKC seems to have shared some important features with siliciclastic sediments that occur within the SCC and elsewhere in Gondwana during the Cambrian Period. Dramatic changes in detrital zircon spectra in a given tectonostratigraphic terrane (over ca. 40 Myr) may be a result of provenance changes due to variations of depositional environment and sedimentary processes (e.g., Zimmermann et al. 2015). Coarse-grained sandstones of the Jangsan, Myeonsan, and Dongjeom formations in the Taebaek Group were deposited mainly in shallow marine coastal to nearshore environments. The sediments were supplied directly from the underlying basement by erosion during transgression and/or from nearby regional fluvial drainage systems and then transported by longshore drift along the shoreline (Fig. 9; Johnsson 1993). Conversely, the fine-grained sandstones of the Myobong and Sesong formations were generally deposited in inner to outer shelf environments (Fig. 9), with sediments sourced from a wider area (e.g., Potter et al. 2005). This is analogous to the modern Yellow Sea, located between China and the Korean Peninsula, where detrital zircons in sand-size sediments on the Korean coast originated from the Korean Peninsula, whereas those in offshore silt/mud-size sediments (in the central region of the Yellow Sea) are supplied from mainland China via the Yellow River (Huang He) and the Yangtze River (Choi et al. 2013).

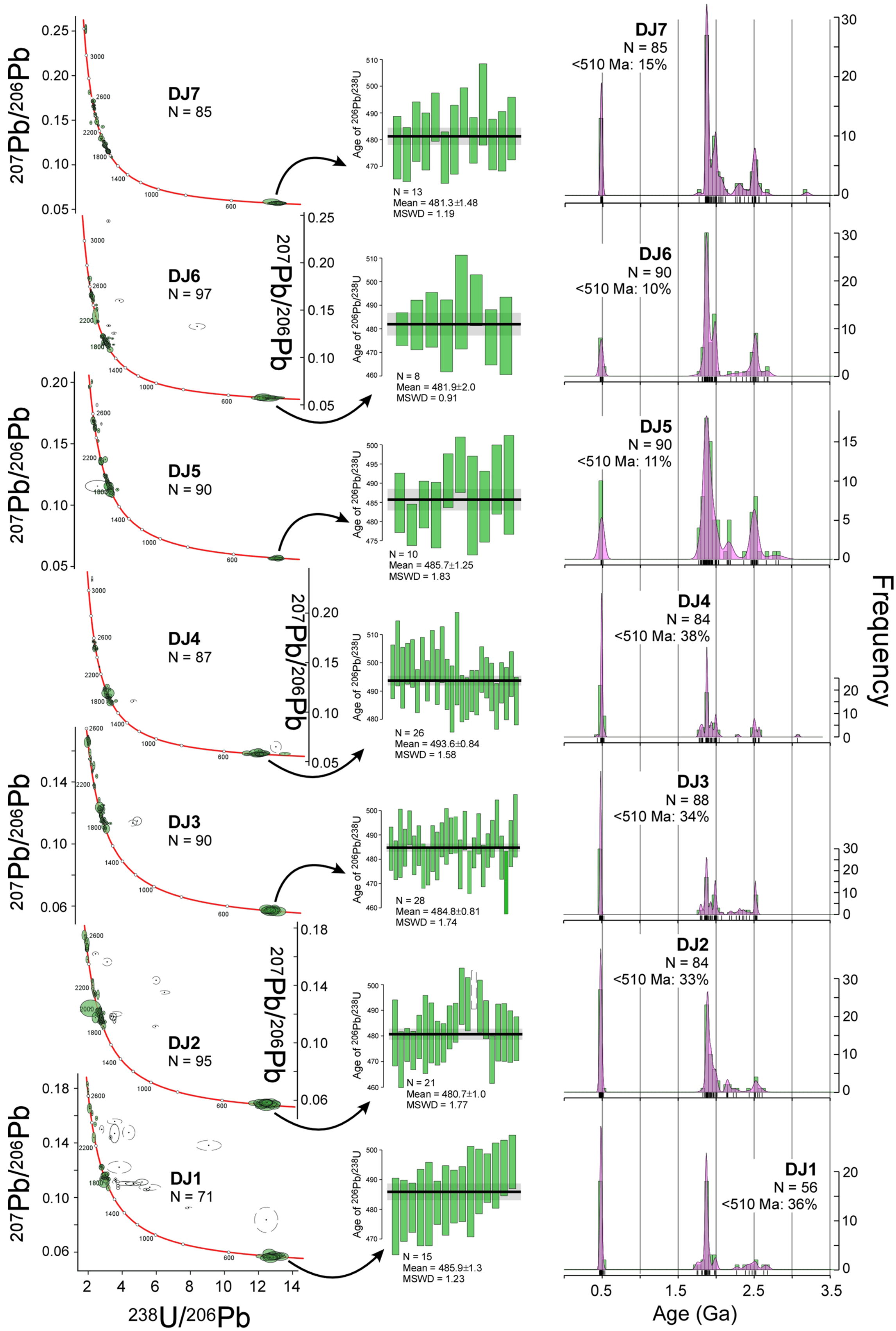
Therefore, it is possible that the repetition of contrasting detrital zircon age spectra in the coarse- and fine-grained sedimentary rocks of the Taebaek Group resulted from changes in the supply and deposition of sediment from two different provenances (Fig. 9). The provenance of detrital zircon from coarse-grained sandstones (Jangsan and Myeonsan formations) is closely associated with basement units in the SKC. Conversely, detrital zircon ages from fine-grained sandstones (Myobong and Sesong formations) are contemporaneous with the Grenville orogeny (Scotese 2009) and the breakup of the Rodinia supercontinent (Evans 2009), indicating a Gondwanan affinity and/or Neoproterozoic supra-crustal rocks of the GMB (Cho and Cheong 2016).

Implications for paleogeography and tectonic implications of the early Paleozoic Sino-Korean Craton

Both the SKC and SCC were located near the northern margin of Gondwana (adjacent to what is now India and Australia) during the early Paleozoic (Fig. 1). Of note, the age spectra of detrital zircons similar to those documented in the Taebaek Group are present throughout the SKC. For example, coarse-grained Cambrian–Ordovician sedimentary rocks from the Ordos Basin in the western part of the SKC exhibit detrital zircon ages (Fig. 12; Darby and Gehrels 2006; Wang et al. 2016) similar to those of the Myeonsan, Jangsan, and Dongjeom formations (Figs. 9, 11). Furthermore, age populations of detrital zircons from the Myobong and Sesong formations are comparable to those of coeval successions in the southwestern SKC (Mantou Formation, Shaanxi Province; McKenzie et al. 2011), central SKC (Xuzhuang Formation, Beijing area; Hu et al. 2013), northwestern SKC (Lashizhong Formation; Wang et al. 2016), and marginal SKC (Sambangsan Formation, Yeongwol Group; Kim et al. 2013; Jang et al. 2018) (Figs. 9, 12). These observations suggest that a significant volume of fine-grained sediment was transported from mainland Gondwana and dispersed throughout the SKC and the surrounding area during the Cambrian to middle Ordovician (Meng et al. 1997), although further studies are necessary on how the SKC was occupied around the Gondwana during the early Paleozoic, and how fine-grained sediments were transported long distance from the Gondwana.

The proportion of younger magmatic zircons is highly variable in the Cambrian–Early Ordovician (520–470 Ma) siliciclastic rocks. In the Cambrian sequences, less than 4% of detrital zircons were derived from early Paleozoic magmatic activity, in sharp contrast to values up to 38% in the Lower Ordovician Dongjeom Formation (Figs. 9, 11). In addition, the late Mesoproterozoic (1300–900 Ma) and Neoproterozoic (650–550 Ma) peaks dominate in fine-grained siliciclastic rocks from the SKC, but are absent in coarse-grained sandstones deposited in the SKC during the Early Ordovician (Figs. 9, 12). The remarkable changes in detrital zircon ages and grain size of sediments may be attributed to a provenance shift related to rifting and/or magmatic activity in an arc setting around the margin of Gondwana (Zhu et al. 2012; Li et al. 2017). Wang et al. (2016) also documented similar changes in coarse sandstones (deposited in the shoreline and nearshore) and siltstone (deposited in deep sea; Fei 2001) of the Ordovician Sandaokan and Lashizhong formations, respectively, in the western SKC (Fig. 12). They proposed that the marked contrast in detrital zircon age spectra probably resulted from provenance shift. Crystalline basements rocks in the northwestern SKC and the Neoproterozoic belt between the western SKC and the eastern Gondwana may be the main provenances of the Sandaokan and Lashizhong formations, respectively.

Consequently, the age spectra of detrital zircon in siliciclastic sedimentary rocks can be influenced by the provenance changes combined with depositional environment. Despite approximately coeval deposition during the


DJ7
N = 85
N = 13
Mean = 481.3±1.48
MSWD = 1.19
DJ7
N = 85
<510 Ma: 15%
DJ6
N = 97
N = 8
Mean = 481.9±2.0
MSWD = 0.91
DJ6
N = 90
<510 Ma: 10%
DJ5
N = 90
N = 10
Mean = 485.7±1.25
MSWD = 1.83
DJ5
N = 90
<510 Ma: 11%
DJ4
N = 87
N = 26
Mean = 493.6±0.84
MSWD = 1.58
DJ4
N = 84
<510 Ma: 38%
DJ3
N = 90
N = 28
Mean = 484.8±0.81
MSWD = 1.74
DJ3
N = 88
<510 Ma: 34%
DJ2
N = 95
N = 21
Mean = 480.7±1.0
MSWD = 1.77
DJ2
N = 84
<510 Ma: 33%
DJ1
N = 71
N = 15
Mean = 485.9±1.3
MSWD = 1.23
DJ1
N = 56
<510 Ma: 36%
207Pb/206Pb
238U/206Pb
Age of 206Pb/238U
Age (Ga)
Frequency

◂**Fig. 11** Terra-Wasserburg and probability diagrams showing U–Pb detrital zircon ages combined with a weighted mean $^{206}Pb/^{238}U$ age of the younger concordant ages in the Dongjeom Formation (DJ1–DJ7)

Cambrian–Early Ordovician, there are marked differences between detrital zircon age populations in coarse- and fine-grained siliciclastic sedimentary rocks within the Taebaek Group. Thus, fundamental sedimentary information, including sediment grain size, provenance, and depositional environment, should be fully integrated into detrital zircon geochronological studies to avoid misinterpretation of the tectonic evolution of a region (e.g., Lawrence et al. 2011; Zimmermann et al. 2015). By considering these factors, it may be possible to generate increasingly precise provenance and paleogeographic models of stable epeiric platforms. Further studies based on detrital zircons from additional localities, considering different lithologies, will enhance our understanding of the spatial and temporal evolution of sediment provenance. This will also serve to elucidate the previously uncertain paleogeographic location of the Sino-Korean Block relative to other peri-Gondwana terranes.

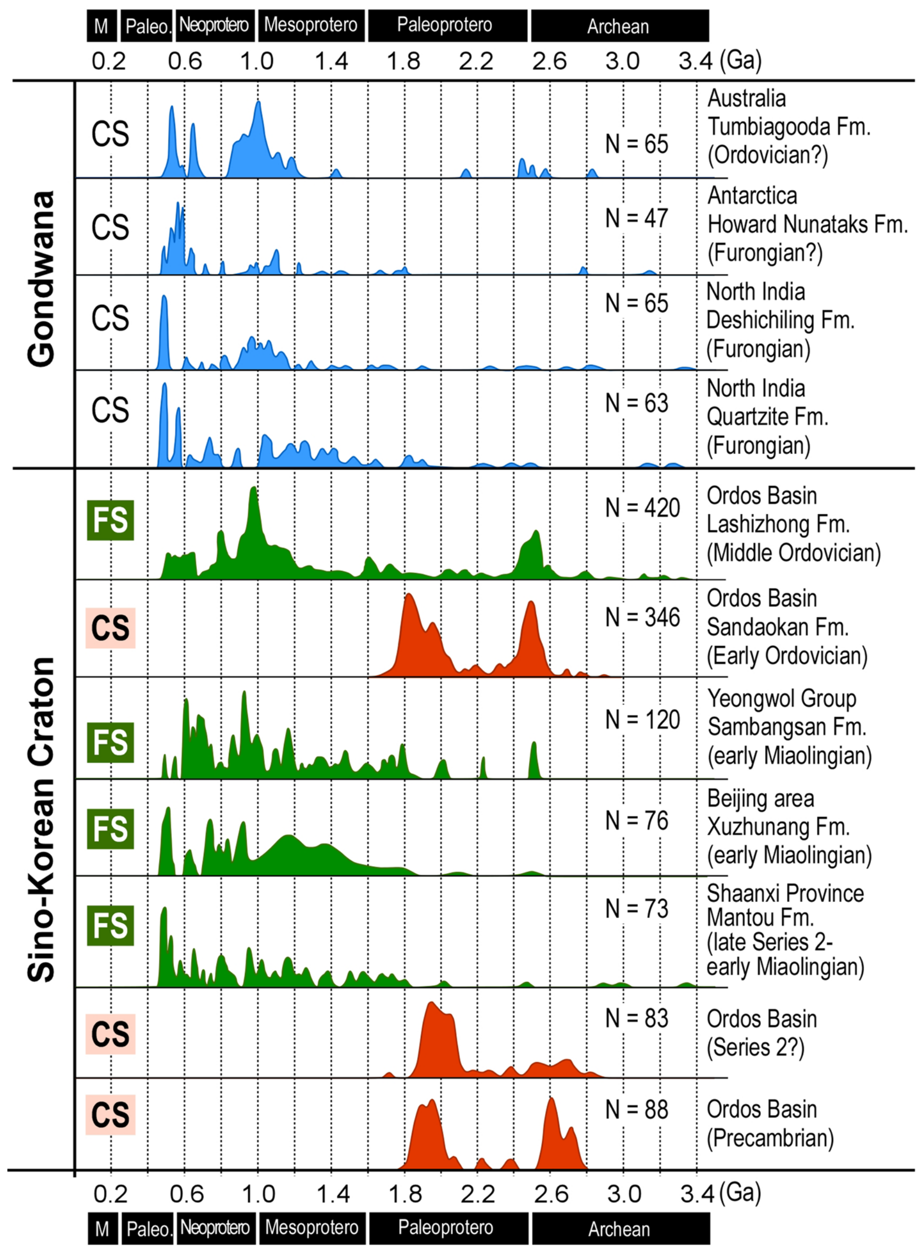


Fig. 12 Summary of the concordant age populations of detrital zircons from various locations on the Sino-Korean Block and Gondwana. Detrital zircon ages of the Precambrian, Cambrian–Ordovician sedimentary rocks in the Sino-Korean Block and the Gondwana supercontinent are from Ordos Basin (Darby and Gehrels 2006; Wang et al. 2016), Shanxi Province (McKenzie et al. 2011), Yeongwol Group (Kim et al. 2013; Jang et al. 2018), Beijing area (Hu et al. 2013), North India (McKenzie et al. 2011), Antarctica (Flowerdew et al. 2007), and Australia (Cawood and Nemchin 2000). Abbreviations are same as those in Fig. 9

Conclusions

Detrital zircons from the Lower Ordovician Dongjeom Formation in the Taebaek Group preserve a unique age spectrum: Archean–Paleoproterozoic (~ 1900 Ma) and late Cambrian–Early Ordovician (~ 500 Ma) peaks. This indicates that sediments of the formation were derived from both the SKC and/or Gondwana. The younger, angular detrital zircon grains were likely derived from a proximal source comprising a rift and/or magmatic arc at the Gondwana margin. Furthermore, integration of detrital zircon results with characteristic grain sizes of sediments, source rocks, and water depth changes within Cambrian–Ordovician sequences in the SKC indicates that the ages of detrital zircon populations deposited in stable epeiric platforms are influenced by sedimentary processes, even in the absence of significant tectonic activity.

Coarse-grained sandstones in the Taebaeksan and Ordos basins were sourced mainly from nearby Paleoproterozoic–Neoarchean basement rocks of the SKC. Fine-grained sediments of the Cambrian–Ordovician siliciclastic formations in the SKC were transported from mainland Gondwana and deposited over vast areas of the SKC. Our study, therefore, indicates that the SKC had a closer affinity to Gondwana during the Cambrian to Ordovician than previously suggested. The results also emphasize the need for sedimentary processes to be considered prior to the interpretation of detrital zircon ages.

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