

Article

Tectonic Setting of the Eastern Margin of the Sino-Korean Block in the Pennsylvanian: Constraints from Detrital Zircon Ages

Mun Gi Kim ¹, Yong Il Lee ^{2,*} and Taejin Choi ³¹ Global Ocean Research Center, Korea Institute of Ocean Science & Technology, Busan 49111, Korea; mgkim@kiost.ac.kr² School of Earth and Environmental Sciences, Seoul National University, Seoul 08826, Korea³ Department of Energy Resources Engineering, Chosun University, Gwangju 61542, Korea; tchoi@chosun.ac.kr

* Correspondence: lee2602@plaza.snu.ac.kr

Received: 20 April 2020; Accepted: 8 June 2020; Published: 9 June 2020



Abstract: To test the previous hypothesis that upper Paleozoic sediments in the eastern Sino-Korean Block were mostly derived from the paleo-orogen located to the east, we compared published and new U–Pb age data of detrital zircons from Pennsylvanian strata distributed in the Sino-Korean Block (SKB). The age distributions of detrital zircons from different localities of Pennsylvanian strata in North China reflect varying contributions from the Inner Mongolia Paleo-uplift in the north and the Central China Orogenic Belt in the south. The supply of detritus from the northern source to distant areas, however, appears to have been limited during the Pennsylvanian times. The age distributions of detrital zircons from Korean Pennsylvanian strata located in the east of the SKB are characterized by a dense cluster of 1.84–1.90 Ga and differ from those of North China. The Korean age characteristic is best explained by strong influences of the detritus derived from the Paleoproterozoic Yeongnam Massif in southeastern Korea. Along with the significant number of zircons that record syn- to near-depositional magmatic activities, this observation supports the hypothesis of the existence of an active continental margin setting in the east of the SKB.

Keywords: Pennsylvanian; Sino-Korean Block; provenance; detrital zircons; U–Pb ages

1. Introduction

Detrital zircon U–Pb geochronology has greatly improved our understanding on the late Paleozoic tectonic evolution of the Sino-Korean Block (SKB; also called the North China Block). The upper Paleozoic succession in North China, particularly its lowermost strata deposited upon the Late Ordovician–Pennsylvanian unconformity, has been rigorously analyzed in many different localities [1–6]. Results pointed to two major source terrains, each carrying the “northern” and “southern” signatures in the U–Pb age and Hf isotopic composition of detrital zircons: the uplifted northern margin of the SKB, commonly referred to as the Inner Mongolian Paleo-uplift (IMPU), and the Central China Orogenic Belt (CCOB) including the North Qinling Block (NQB) in the south, respectively (Figure 1). It is increasingly accepted that both northern and southern terrains had contributed detritus significantly to the Pennsylvanian deposits [7], while the former had dominant influence on the overlying Permian deposits [8,9]. Wang et al. [7] described the Pennsylvanian depositional setting as a “walled continental basin”, which was set before the Permian southward tilt of the basin due to further uplift in the north [10].

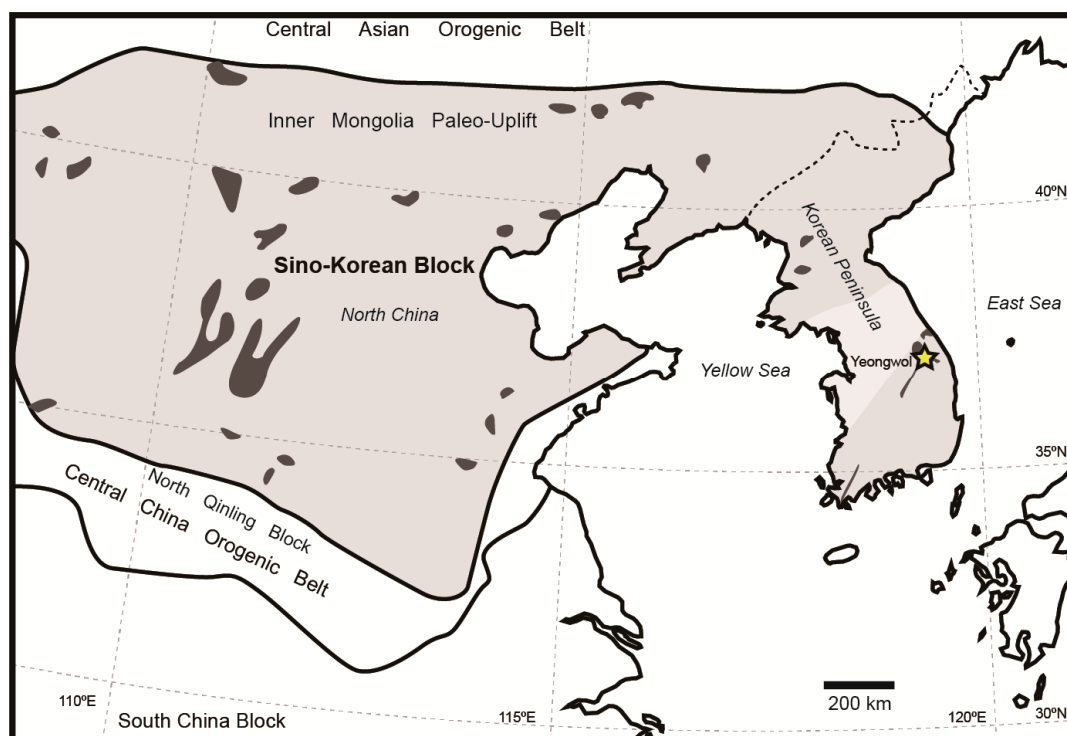


Figure 1. Simplified tectonic map of the Sino-Korean Block (gray color). Light gray color in the Korean Peninsula represents the tectonic provinces under debate. Dark gray color outlines the distribution of Pennsylvanian strata in the Sino-Korean Block (modified from [11,12]). Yellow star indicates the Yeongwol site where the newly analyzed sample was obtained.

Paleozoic sedimentary successions in Korea are well correlatable to the equivalent strata in North China [13–20], and thus they are widely recognized as being deposited on the SKB in various tectonic models [21–24]. For the upper Paleozoic sediments in the southeastern Korean Peninsula, the eastern derivation of detritus in a foreland basin setting has long been assumed based on paleocurrent directions and sandstone composition [25–28]. Recent detrital zircon provenance studies have also supported the presence of an active continental margin setting that had formed in the east [29–31]. However, as many previous detrital zircon provenance studies conducted in North China interpreted their results simply upon north-south cross-section, the possible eastern source has been commonly overlooked in the large-scale discussions on the SKB.

This study proposes the existence of a ‘third wall’ in the east of the SKB during the Pennsylvanian, probably formed by the subduction of the paleo-Pacific plate beneath the eastern margin of the SKB [32,33]. The general framework of this setting has been put forward earlier by Kim and Lee [20]. In this study, we elaborate the idea further by comprehensively comparing the detrital zircon age populations reported from Pennsylvanian deposits spread over the SKB, with particular focus on their localities in the eastern side of the block. The Pennsylvanian sediments in the SKB, the oldest upper Paleozoic sedimentary strata deposited before the dominance of northern signature in the Permian, provide the most suitable time record that can distinguish the potential eastern contribution.

2. Geological Background and Methods

The SKB is bounded to the north by the Central Asian Orogenic Belt (CAOB) and to the south by the CCOB (Figure 1). Tectonic evolution of the southern CAOB is not fully understood, but there is a broad consensus that the Paleo-Asian Ocean subducted southward beneath the northern margin of the SKB during the Pennsylvanian–Permian times [34–36], which led to the uplifting and exhumation of the IMPU [8,37]. The timing of complicated accretionary and collisional processes in

the CCOB is also controversial, but it is widely accepted that the NQB, the northern part of CCOB, had formed highlands along the southern margin of the SKB, at least by the Carboniferous [38–40]. Taking these into account, many previous studies on the provenance of upper Paleozoic sediments in North China considered the IMPU and the CCOB as two primary potential source regions [8,9,41]. Archean–Paleoproterozoic basement rocks intruded by Devonian–Triassic plutons are widely exposed in the IMPU [35,42], whereas multiple orogenies in the Meso- to Neoproterozoic and early Paleozoic times are recorded in the highly metamorphosed rock assemblages in the CCOB [43,44].

The Paleozoic of the SKB is mostly represented by the Cambrian–Middle Ordovician marine sediments and the Pennsylvanian–Triassic paralic to non-marine sediments. A regional unconformity spanning more than 100 Ma separates the lower and upper Paleozoic sequences (Figure 2). In North China, the basal stratigraphic unit of the upper Paleozoic succession is named the Benxi Formation. In South Korea, it is called the Manhang Formation (and locally, the Yobong Formation). Both the Benxi and Manhang formations are composed of siliciclastic sediments with some intercalated limestones, and are unconformably underlain by Middle Ordovician limestones. The average thicknesses of the Benxi and Manhang formations are known to be 10–150 m and 100–300 m, respectively, although they reach more than 1 km in a few localities [10,20]. Correlatable fusulinid zones and floral assemblages have been established for both formations, and indicate that they are Bashkirian–Moscovian (early Pennsylvanian) in age [45–48]. However, in some localities in northern North China, several detrital zircon grains that were dated as young as the earliest Permian times have been reported from the Benxi Formation [2,37]. This might be due to the fact that the lowermost strata of the upper Paleozoic succession are partly diachronous across the SKB [49] (Figure 2).

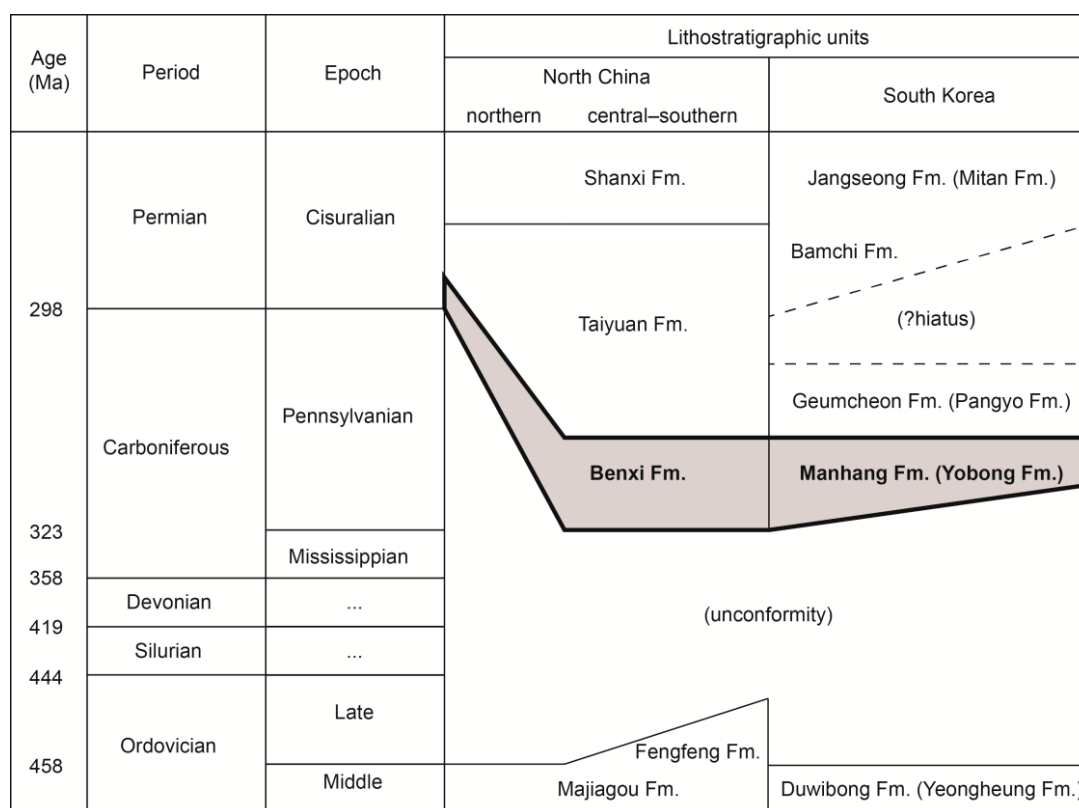


Figure 2. Middle Ordovician–Early Permian (Cisuralian) stratigraphy of North China and South Korea (modified from references [20,49,50]). The gray color represents the strata from which the detrital zircon U–Pb age data were obtained.

From the literature, we obtained data on the detrital zircon U–Pb age of the Pennsylvanian deposits from two localities in South Korea and 19 localities in North China. Data collection was

limited to the lowermost units of the upper Paleozoic succession (Figure 2). Three localities of the Benxi Formation of possible earliest Permian age are included; however, caution needs to be exercised when interpreting data derived from strata known to have such young ages. In addition to the literature data, we analyzed detrital zircon U–Pb ages of one sandstone sample collected from the basal part of the Yobong Formation in the Yeongwol area of central eastern Korea (Figure 1). Analytical methods for detrital zircon U–Pb dating of the Yobong Formation sample are presented in Appendix A.

The collected literature and newly obtained age data were processed under the same measure for accurate comparison of multiple dataset. For detrital zircon grains younger and older than 1000 Ma, ^{238}U – ^{206}Pb dates and ^{207}Pb – ^{206}Pb dates, respectively, were used for interpretation. Consistent discordance cut (exclusion of ages with normal or reverse discordance >10%) was applied. Discordance was calculated based on the difference between ^{238}U – ^{206}Pb and ^{235}U – ^{207}Pb dates ($1 - (^{238}\text{U}\text{--}^{206}\text{Pb} \text{ date} / ^{235}\text{U}\text{--}^{207}\text{Pb} \text{ date})$) for detrital zircon grains younger than 1000 Ma, and that between ^{238}U – ^{206}Pb and ^{206}Pb – ^{207}Pb dates ($1 - (^{238}\text{U}\text{--}^{206}\text{Pb} \text{ date} / ^{206}\text{Pb}\text{--}^{207}\text{Pb} \text{ date})$) for those older than 1000 Ma. Few grains with apparent ages that passed the discordance cut, but were undeniably younger (e.g., 288 ± 2 Ma at the Taebaek locality and 182 ± 21 Ma at the Pingquan locality) than the upper limit of depositional age (Figure 2), or had excessively large analytic errors (e.g., 1594 ± 105 Ma) were removed from further consideration. Only age data meeting all the listed criteria were used for plotting and interpretation.

3. Results

A total number of 1669 concordant or slightly discordant zircon U–Pb ages, including 49 newly analyzed ages (Table S1), were obtained from the Pennsylvanian strata at 22 localities in the SKB. A summary of the combined detrital zircon ages is presented in Figure 3. Six major age populations were identified: (1) Carboniferous (ca. 310 Ma); (2) Devonian (ca. 390 Ma); (3) Ordovician–Silurian (ca. 440 Ma); (4) Neo- to Mesoproterozoic (a notable peak at ca. 960 Ma with several subordinate peaks); (5) Late Paleoproterozoic (a wide peak centering at ca. 1870 Ma with a subsidiary peak at ca. 1930 Ma), and (6) Early Paleoproterozoic to Neoarchean (a broad peak centering at ca. 2500 Ma).

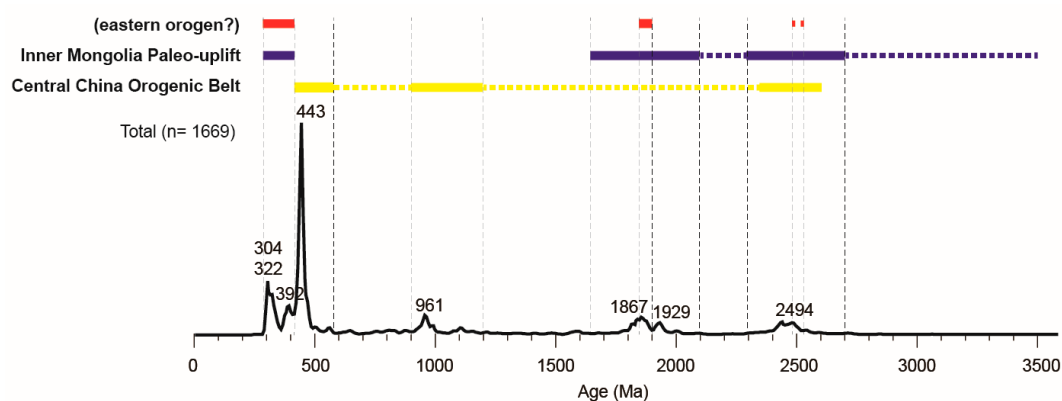


Figure 3. Composite detrital zircon age spectrum (Kernel Density Estimate; Vermeesch [50]) from the Pennsylvanian strata distributed in the Sino-Korean Block. Thick colored lines represent the characteristic age ranges of zircons that are distributed in the respective source terrains, while dotted lines represent that occurring in subordinate amount (modified from Zhu et al. [9]).

Figure 4 summarizes the distributions of detrital zircon ages of the Pennsylvanian strata deposited in sedimentary basins on the SKB, represented by a pie diagram in each studied area. The full age data are available in the online supplementary material (Table S2).

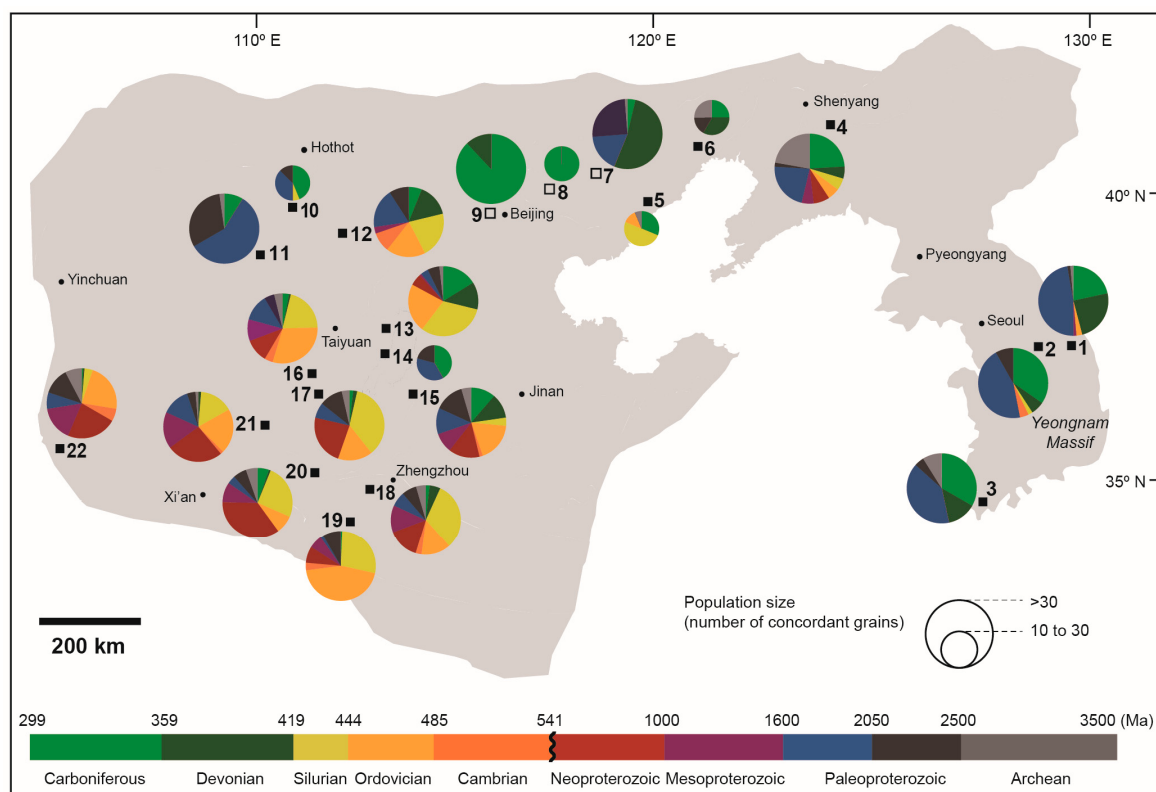


Figure 4. Pie diagrams of detrital zircon age distribution over the Sino-Korean Block. Locations: 1. Taebaek; 2. Yeongwol; 3. Gangjin; 4. Benxi; 5. Qinhuangdao; 6. Nanpiao; 7. Pingquan; 8. Yingshouyingzi; 9. Western Beijing; 10. Qingshuihe; 11. Baode; 12. Shuo Zhou; 13. Yangquan; 14. southern Yangquan; 15. Wu'an; 16. Jinzhong; 17. Changzhi; 18. Gongyi; 19. Lushan; 20. Sanmenxia; 21. Hancheng; 22. Pingliang (see Table S2 for references). The empty rectangles indicate where the Benxi Formation is supposed to be younger (see text for details).

4. Discussion

4.1. Sediment Dispersal over the SKB

4.1.1. Northern vs. Southern Signature

It is generally agreed that the Carboniferous, Devonian, and Late Paleoproterozoic zircon grains represent the northern signature derived from the IMPU, whereas the Ordovician–Silurian (with negative $\varepsilon_{\text{Hf}}(t)$) and Neo- to Mesoproterozoic components represent the southern signature derived from the CCOB [7–9,40], although such occurrences are not completely exclusive to each other. In this regard, grains with the northern signature dominantly occur in areas close to the northern margin (sites 6–11 in Figure 4). The Silurian to Mesoproterozoic grains mainly occupy the zircon population in central to southern North China (sites 13–22), suggesting a sediment supply from the south. Such distinct distributions of detrital zircon ages clearly show that competing northern and southern signatures are reflected in Pennsylvanian deposits in North China.

Notably, the southern signature is visible at several northern sites, including the Benxi and Qinhuangdao sites in northeastern China (sites 4 and 5), as well as the Shuo Zhou site in north-central China (site 12). The occurrence of ca. 440 Ma zircon grains characterized by negative $\varepsilon_{\text{Hf}}(t)$ in northern localities was deemed enigmatic by Liu et al. [2], because they only considered the source rocks in the north. According to Wang et al. [7], these grains may be reinterpreted to have been originated from the NQB. Significant southern signature in these three sites suggests that sediment supply from the north was not dominant. In the frontal region of the eastern IMPU, it has been interpreted that the Benxi Formation was deposited in coast–offshore settings, including fan deltas at the basin margin [49].

Such environmental settings explain both the mixing of northern and southern influences in the distal part (sites 4 and 5) and highly variable detrital zircon age distributions among sites in the proximal part (sites 6–9), suggestive of the northern provenance being of local importance. Besides, some of the zircon age records with the dominant northern signature (sites 7–9) may represent the earliest Permian time instead of the Pennsylvanian (empty rectangles in Figure 4). It is therefore likely that the supply of detritus from the northern margin of the SKB to the distant areas was rather limited during the Pennsylvanian times, particularly in the northeastern side of the block.

4.1.2. Potential Eastern Signature

Based on the interpretation above, the northern signature-like detrital zircons from the Pennsylvanian strata in southern Korea (sites 1–3) located in the eastern margin of the SKB are difficult to interpret as being derived from the north. Consistent age distribution patterns are observed in Taebaek, Yeongwol, and Gangjin localities (Figure 5a): major age groups at ca. 320 Ma and ca. 1.85 Ga, and minor groups at ca. 390 Ma and ca. 2.5 Ga. The lack of southern signature is understandable considering that these sites were located relatively far from the NQB. Given the presumed setting in northern North China during the Pennsylvanian times, however, major sediment supply from the northern margin of the SKB is not plausible, since it has to account for the large amount of sediments reaching several hundred meters thick in these distant sites. An alternative explanation for the source terrain is then required.

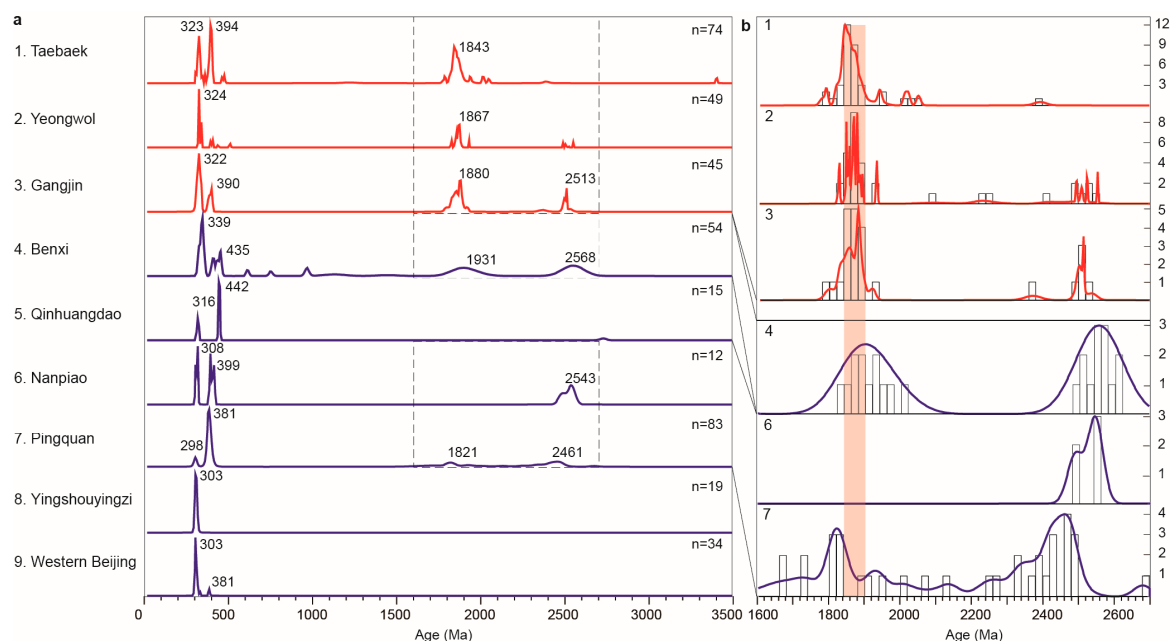


Figure 5. Probability density plot and age histograms of detrital zircons from the Pennsylvanian strata in the eastern part of the Sino-Korean Block: (a) full age spectra, and (b) enlarged views of the Neoproterozoic–Paleoproterozoic portion for selected localities. See Figure 4 for site locations.

Close looking into the Paleoproterozoic–Neoproterozoic age groups provides an important clue (Figure 5b). Records from northern North China exhibit wide variance of Paleoproterozoic–Neoproterozoic ages. The Pennsylvanian strata in Korea, in contrast, are characterized by a vast majority of Precambrian grains belonging to narrow time spans of 1.84–1.90 Ga and 2.48–2.54 Ga, with the former being more abundant than the latter. This observation is in line with a previous report on composite detrital zircon ages of Upper Paleozoic sediments in southern Korean Peninsula [18]. The consistency of 1.84–1.90 Ga peak in all three localities in Korea suggests a regional characteristic, a signature that is best explained by derivative sediments from the Precambrian massifs in the Korean Peninsula, particularly the Yeongnam Massif located in the southeast. Besides the widespread distribution of basement rocks

with these ages [51,52], sediments from the Nakdong River that drains the Yeongnam Massif prove that the Yeongnam Massif indeed provides detritus that is dominantly composed of 1.84–1.90 Ga detrital zircons [53]. This feature is distinct from the age characteristics of zircons from river sediments of the Yongding and Luan rivers in eastern North China. Both latter rivers have a drainage area similar to the Nakdong River, but their sediments contain much heterogeneous Paleoproterozoic detrital zircon population [54]. In summary, the detrital zircon ages of the Pennsylvanian sediments in Korea may, at first glance, be thought to have been derived from the IMPU, but are much likely to have been derived from another source terrain.

4.2. Tectonic Implications

In general, the significant proportion of zircon grains that were young at the time of deposition is considered as the characteristic of a basin close to the convergent plate margin [55]. In a situation where major supplies from the northern and southern sources are not likely, another orogenic belt for Pennsylvanian strata in the Korean Peninsula could be set to the east (Figure 6). This interpretation is in agreement with the paleocurrent directions and inferred basin topography [25–27,56], and better explains the generally euhedral shape of syndepositional zircons (Figure A1). Some of these Carboniferous zircons also exhibit high Th/U values (Figure 7), which is typical of the zircons derived from intermediate to mafic igneous rocks [57–59]. Previous detrital zircon provenance studies in different localities in Korea [29–31] also favored the same interpretation. Our interpretation of the eastern source terrains is supported by the hypothesis of previous studies that the subduction of the paleo-Pacific plate took place beneath the eastern margin of the SKB during the Late Paleozoic [32,33]. Wider acceptance of this hypothesis is currently hindered by the limited occurrence of Pennsylvanian plutons in the east, but some evidence for Pennsylvanian magmatism can be found in the Hida Belt [60–62], a continental fragment in Japan [63]. Even if the subduction had taken place in the eastern margin of the SKB, corresponding plutons might have been largely removed by later rapid uplift of widespread Jurassic plutons (i.e., [64]), Cretaceous sedimentation in southeastern Korea, and Upper Cretaceous regional exhumation of the Korean Peninsula [65] and the Japanese islands [66]. Recent U–Pb zircon age analysis on paragneiss in the Hida Belt reported inherited/detrital core ages that cluster at ca. 300 and 330 Ma, which also accompany Paleoproterozoic zircon grains that almost entirely fall within 1.81–1.90 Ga [67]. This finding is highly significant considering the pre-Cenozoic configuration of the Hida–Oki Belt in Japan, which is believed to have been attached to the east of the Korean Peninsula before the opening of the East Sea (Sea of Japan) [66,68,69].

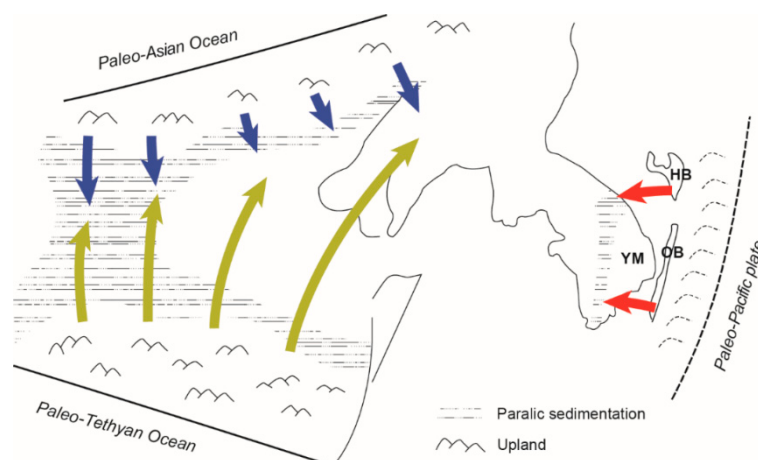


Figure 6. Sediment dispersal patterns and inferred paleogeography and tectonic configuration of the Sino-Korean Block (SKB) during the Pennsylvanian (modified from Liu [10]). YM = Yeongnam Massif, HB = Hida Belt, OB = Oki Belt. Tectonic blocks are reconstructed to their inferred original position before the Tanlu fault-movement and the opening of the East Sea (Sea of Japan).

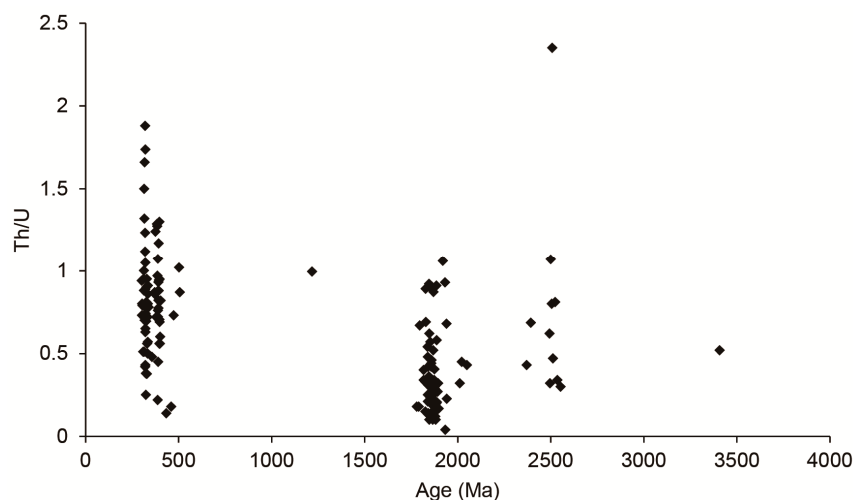


Figure 7. Th/U vs. Age plot for detrital zircon grains from the Pennsylvanian Yobong Formation in the Yeongwol area, central eastern Korea.

Based on our new perspective, it is also noteworthy that the same characteristic 1.84–1.90 Ga-aged zircons consistently dominate the detrital zircon populations throughout the overlying Permian–Lower Triassic strata in Korea [31,70,71], whereas detrital zircons from the coeval successions in North China generally show much wider spread of ca. 1.9 Ga peak and larger portion of ca. 2.5 Ga peak [9,37,72]. This comparison suggests that (1) high concentration in the 1.84–1.90 Ga range is the unique signature of the eastern source terrain and (2) its influence on the proximal areas remained constant throughout late Paleozoic times. How far this sedimentation regime in the east had expanded further to the inner part of the SKB is unknown at present, partly due to the lack of data in areas adjacent to the western Korean Peninsula. Overlap in U–Pb ages and $\varepsilon_{\text{Hf}}(t)$ values of the Yeongnam Massif zircons (i.e., as reported previously [52]) with those of the IMPU makes it difficult to evaluate how much contribution was from the eastern sources, but our findings may prove useful in case where the eastern signature is suspected to occur. Reinterpretation of the existing detrital zircon U–Pb age data and future studies on the upper Paleozoic strata in the SKB, especially for the eastern North China, are recommended to take this potential contribution from the east into account.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2075-163X/10/6/527/s1>, Table S1: LA-ICP-MS U–Pb dating data of detrital zircons from Yobong Formation sample; Table S2: Detrital zircon U–Pb ages of Pennsylvanian sediments in the Sino-Korean block.

Author Contributions: Conceptualization, M.G.K. and Y.I.L.; formal analysis, M.G.K.; investigation, M.G.K. and T.C.; resources, T.C.; writing—original draft preparation, M.G.K.; writing—review and editing, Y.I.L. and T.C.; visualization, M.G.K.; supervision, Y.I.L.; funding acquisition, Y.I.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Research Foundation of Korea, grant number 2014R1A2A2A01005404 to YIL and grant number 2012H1A2A1049032 to MGK. MGK also acknowledges support from the Korea Institute of Ocean Science & Technology (PE99824).

Acknowledgments: We thank the Editors, Wilfried Winkler and Albrecht von Quadt, and two anonymous journal reviewers for their constructive comments on our manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Zircon grains were extracted from a sandstone sample, by following the conventional heavy mineral separation methods. After hand picking under binocular microscope, 100 randomly selected zircon grains were embedded in a PFA teflon sheet. Cathodoluminescence (CL) images of each grain were obtained by using a scanning electron microscope (JEOL JSM-5400, JEOL, Akishima, Japan). U–Pb dating of zircons was conducted by using laser ablation inductively coupled plasma mass spectrometry

(LA-ICP-MS) housed at the Korea Basic Science Institute (Cheongju, Korea, Nu Plasma II MC ICP-MS). Detailed instrumental settings and analytical procedures are similar to those described by Lee et al. [73]. Laser ablation was conducted at a spot size of 15 μm , energy density of 2–3 J/cm^3 , and pulse repetition rate of 5 Hz. The reference zircon 91,500 was used as the primary standard [74] and Plesovice as the secondary standard. A single spot per grain was analyzed. Magmatic rim with oscillatory zoning was preferred to core when selecting a spot for the age dating of zircon grains, unless the mixing of different age domain was concerned. Metamorphic overgrowths were not usually present, and were not analyzed (Figure A1).

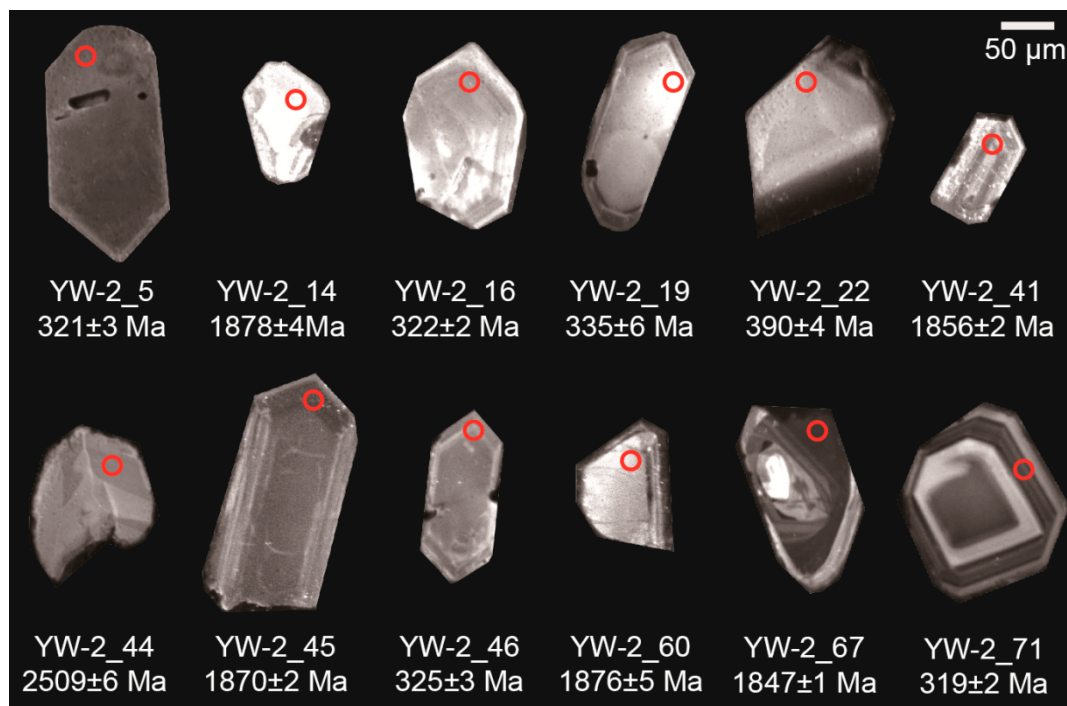


Figure A1. Representative SEM-CL images of detrital zircon grains from the Yobong Formation in the Yeongwol area, central eastern Korea.

References

1. Wang, Y.; Zhou, L.; Zhao, L.; Ji, M.; Gao, H. Palaeozoic uplands and unconformity in the North China Block: Constraints from zircon LA-ICP-MS dating and geochemical analysis of Bauxite. *Terra Nova* **2010**, *22*, 264–273. [\[CrossRef\]](#)
2. Liu, J.; Zhao, Y.; Liu, A.; Zhang, S.; Yang, Z.; Zhuo, S. Origin of Late Palaeozoic bauxites in the North China Craton: Constraints from zircon U–Pb geochronology and in situ Hf isotopes. *J. Geol. Soc.* **2014**, *171*, 695–707. [\[CrossRef\]](#)
3. Cai, S.; Wang, Q.; Liu, X.; Feng, Y.; Zhang, Y. Petrography and detrital zircon study of late Carboniferous sequences in the southwestern North China Craton: Implications for the regional tectonic evolution and bauxite genesis. *J. Asian Earth Sci.* **2015**, *98*, 421–435. [\[CrossRef\]](#)
4. Zhao, L.; Liu, X. Metallogenic and tectonic implications of detrital zircon U–Pb, Hf isotopes, and detrital rutile geochemistry of late carboniferous karstic bauxite on the southern margin of the North China Craton. *Lithos* **2019**, *350–351*, 105222. [\[CrossRef\]](#)
5. Jia, L.; Zhong, D.; Sun, H.; Yan, R.; Zhang, C.; Mo, W.; Qiu, C.; Dong, Y.; Li, B.; Liao, G. Sediment provenance analysis and tectonic implication of the Benxi Formation, Ordos Basin. *Acta Sediment. Sin.* **2019**, *37*, 1087–1103. (In Chinese)

6. Wang, A.-Q.; Yang, D.-B.; Yang, H.-T.; Mu, M.-S.; Quan, Y.-K.; Hao, L.-R.; Xu, W.-L. Late Palaeozoic tectonic evolution of the southern North China Craton: Constraints from detrital zircon dating and Hf–O isotopic compositions of the Benxi Formation, Sanmenxia area, North China Craton. *Geol. J.* **2020**, *55*, 1320–1331. [\[CrossRef\]](#)
7. Wang, Q.; Deng, J.; Liu, X.; Zhao, R.; Cai, S. Provenance of Late Carboniferous bauxite deposits in the North China Craton: New constraints on marginal arc construction and accretion processes. *Gondwana Res.* **2016**, *38*, 86–98. [\[CrossRef\]](#)
8. Li, H.-Y.; He, B.; Xu, Y.-G.; Huang, X.-L. U–Pb and Hf isotope analyses of detrital zircons from Late Paleozoic sediments: Insights into interactions of the North China Craton with surrounding plates. *J. Asian Earth Sci.* **2010**, *39*, 335–346. [\[CrossRef\]](#)
9. Zhu, X.-Q.; Zhu, W.-B.; Ge, R.-F.; Wang, X. Late Paleozoic provenance shift in the south-central North China Craton: Implications for tectonic evolution and crustal growth. *Gondwana Res.* **2014**, *25*, 383–400. [\[CrossRef\]](#)
10. Liu, G. Permo–Carboniferous paleogeography and coal accumulation and their tectonic control in the North and South China continental plates. *Int. J. Coal. Geol.* **1990**, *16*, 73–117. [\[CrossRef\]](#)
11. Yang, Z. The Carboniferous system. In *The geology of China*; Yang, Z., Cheng, Y., Wang, H., Eds.; Oxford University Press: New York, NY, USA, 1986; pp. 102–112.
12. Lee, C.Z. The Late Paleozoic strata. In *Geology of Korea*; Cheng, C.H., Ed.; Sigma Press: Seoul, Korea, 1999; pp. 129–203.
13. Doh, S.-J.; Piper, J.D.A. Palaeomagnetism of the (Upper Palaeozoic–Lower Mesozoic) Pyongan Supergroup, Korea: A Phanerozoic link with the North China Block. *Geophys. J. Int.* **1994**, *117*, 850–863. [\[CrossRef\]](#)
14. Jeong, H.; Lee, Y.I. Late Cambrian biogeography: Conodont bioprovinces from Korea. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2000**, *162*, 119–136. [\[CrossRef\]](#)
15. Choi, D.K.; Kim, D.H.; Sohn, J.W. Ordovician trilobite faunas and depositional history of the Taebaeksan Basin, Korea: Implications for palaeogeography. *Alcheringa* **2001**, *25*, 53–68. [\[CrossRef\]](#)
16. Kim, J.H.; Lee, Y.I.; Li, M.; Bai, Z. Comparison of the Ordovician–Carboniferous boundary between Korea and NE China: Implications for correlation and tectonic evolution. *Gondwana Res.* **2001**, *4*, 39–53. [\[CrossRef\]](#)
17. Jeong, H.; Lee, Y.I. Nd isotopic study of Upper Cambrian conodonts from Korea and implications for early Paleozoic paleogeography. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2004**, *212*, 77–94. [\[CrossRef\]](#)
18. Choi, D.K.; Kim, E.Y. Occurrence of Changshania (Trilobita, Cambrian) in the Taebaeksan Basin, Korea and its stratigraphic and paleogeographic significance. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2006**, *242*, 343–354. [\[CrossRef\]](#)
19. Li, Z.; Ni, L.; Xu, J. The Upper Proterozoic–Paleozoic records of sedimentary sequences and detrital zircon geochronology in Korean Peninsula and North China: Implications for tectonic attributes and division. *Acta Petrol. Sin.* **2016**, *32*, 3139–3154.
20. Kim, M.G.; Lee, Y.I. The Pyeongan Supergroup (upper Paleozoic–Lower Triassic) in the Okcheon Belt, Korea: A review of stratigraphy and detrital zircon provenance, and its implications for the tectonic setting of the eastern Sino–Korean Block. *Earth-Sci. Rev.* **2018**, *185*, 1170–1186. [\[CrossRef\]](#)
21. Chough, S.K.; Kwon, S.-T.; Ree, J.-H.; Choi, D.K. Tectonic and sedimentary evolution of the Korean peninsula: A review and new view. *Earth-Sci. Rev.* **2000**, *52*, 175–235. [\[CrossRef\]](#)
22. Ishiwatari, A.; Tsujimori, T. Paleozoic ophiolites and blueschists in Japan and Russian Primorye in the tectonic framework of East Asia: A synthesis. *Isl. Arc* **2003**, *12*, 190–206. [\[CrossRef\]](#)
23. Chang, K.-H.; Zhao, X. North and South China suturing in the east end: What happened in Korean Peninsula? *Gondwana Res.* **2012**, *22*, 493–506. [\[CrossRef\]](#)
24. Cho, M.; Kim, T.; Yang, S.-y.; Yi, K. Paleoproterozoic to Triassic crustal evolution of the Gyeonggi Massif, Korea: Tectonic correlation with the North China craton. In *Linkages and Feedbacks in Orogenic Systems*; Law, R.D., Thigpen, J.R., Mersch, A.J., Stowell, H.H., Eds.; Geological Society of America: Boulder, CO, USA, 2017; pp. 165–198.
25. Kim, H.M. Paleozoic and Mesozoic paleocurrents of the Danyang coalfield district, Korea. *J. Geol. Soc. Korea* **1971**, *7*, 257–276.
26. Kim, H.M. Neritic paleocurrent analysis of Pennsylvanian Tethyan sea at Samcheog coalfield, Korea. *J. Korea Inst. Min. Geol.* **1978**, *11*, 21–38. (In Korean)
27. Lee, Y.I.; Lim, C. Provenance and compositional variance of the Carboniferous Manhang sandstones, central eastern Korea. *J. Geol. Soc. Korea* **1995**, *31*, 637–652.

28. Lee, Y.I.; Sheen, D.-H. Detrital modes of the Pyeongan Supergroup (Late Carboniferous–Early Triassic) sandstones in the Samcheog coalfield, Korea: Implications for provenance and tectonic setting. *Sediment. Geol.* **1998**, *119*, 219–238. [[CrossRef](#)]
29. Kim, H.S.; Ree, J.-H.; Kim, J. Tectonometamorphic evolution of the Permo-Triassic Songrim (Indosinian) orogeny: Evidence from the late Paleozoic Pyeongan Supergroup in the northeastern Taebaeksan Basin, South Korea. *Int. J. Earth Sci.* **2012**, *101*, 483–498. [[CrossRef](#)]
30. Kim, H.S.; Seo, B.; Yi, K. Medium Temperature and Lower Pressure Metamorphism and Tectonic Setting of the Pyeongan Supergroup in the Munkyeong Area. *J. Petrol. Soc. Korea* **2014**, *23*, 311–324. (In Korean) [[CrossRef](#)]
31. Kim, M.G.; Lee, Y.I.; Choi, T.; Orihashi, Y. The tectonic setting of the eastern margin of the Sino-Korean Block inferred from detrital zircon U–Pb age and Nd isotope composition of the Pyeongan Supergroup (late Paleozoic–Early Triassic), Korea. *Geol. Mag.* **2019**, *156*, 471–484. [[CrossRef](#)]
32. Windley, B.F.; Maruyama, S.; Xiao, W.J. Delamination/thinning of sub-continental lithospheric mantle under Eastern China: The role of water and multiple subduction. *Am. J. Sci.* **2011**, *310*, 1250–1293. [[CrossRef](#)]
33. Kusky, T.M.; Windley, B.F.; Wang, L.; Wang, Z.; Li, X.; Zhu, P. Flat slab subduction, trench suction, and craton destruction: Comparison of the North China, Wyoming, and Brazilian cratons. *Tectonophysics* **2014**, *630*, 208–221. [[CrossRef](#)]
34. Zhang, S.-H.; Zhao, Y.; Song, B.; Yang, Z.-Y.; Hu, J.-M.; Wu, H. Carboniferous granitic plutons from the northern margin of the North China block: Implications for a late Palaeozoic active continental margin. *J. Geol. Soc.* **2007**, *164*, 451–463. [[CrossRef](#)]
35. Zhang, S.-H.; Zhao, Y.; Liu, J.-M.; Hu, Z.-C. Different sources involved in generation of continental arc volcanism: The Carboniferous–Permian volcanic rocks in the northern margin of the North China block. *Lithos* **2016**, *240–243*, 382–401. [[CrossRef](#)]
36. Eizenhöfer, P.R.; Zhao, G.; Zhang, J.; Sun, M. Final closure of the Paleo-Asian Ocean along the Solonker Suture Zone: Constraints from geochronological and geochemical data of Permian volcanic and sedimentary rocks. *Tectonics* **2014**, *33*, 441–463. [[CrossRef](#)]
37. Ma, S.; Meng, Q.; Duan, L.; Wu, G. Reconstructing Late Paleozoic exhumation history of the Inner Mongolia Highland along the northern edge of the North China Craton. *J. Asian Earth Sci.* **2014**, *87*, 89–101. [[CrossRef](#)]
38. Dong, Y.; Zhang, X.; Liu, X.; Li, W.; Chen, Q.; Zhang, G.; Zhang, H.; Yang, Z.; Sun, S.; Zhnag, F. Propagation tectonics and multiple accretionary processes of the Qinling Orogen. *J. Asian Earth Sci.* **2015**, *104*, 84–98. [[CrossRef](#)]
39. Liu, L.; Liao, X.; Wang, Y.; Wang, C.; Santosh, M.; Yang, M.; Zhang, C.; Chen, D. Early Paleozoic tectonic evolution of the North Qinling Orogenic Belt in Central China: Insights on continental deep subduction and multiphase exhumation. *Earth-Sci. Rev.* **2016**, *159*, 58–81. [[CrossRef](#)]
40. Yang, D.-B.; Yang, H.-T.; Shi, J.-P.; Xu, W.-L.; Wang, F. Sedimentary response to the paleogeographic and tectonic evolution of the southern North China Craton during the late Paleozoic and Mesozoic. *Gondwana Res.* **2017**, *49*, 278–295. [[CrossRef](#)]
41. Wang, Y.; Yang, W.; Zheng, D.; Zuo, P.; Qi, S. Detrital zircon U–Pb ages from the Middle to Late Permian strata of the Yiyang area, southern North China Craton: Implications for the Mianlue oceanic crust subduction. *Geol. J.* **2019**, *54*, 3527–3541. [[CrossRef](#)]
42. Zhang, S.-H.; Zhao, Y.; Song, B.; Hu, J.-M.; Liu, S.-W.; Yang, Y.-H.; Chen, F.-K.; Liu, X.-M.; Liu, J. Contrasting Late Carboniferous and Late Permian–Middle Triassic intrusive suites from the northern margin of the North China craton: Geochronology, petrogenesis, and tectonic implications. *Geol. Soc. Am. Bull.* **2009**, *121*, 181–200. [[CrossRef](#)]
43. Wang, X.; Wang, T.; Zhang, C. Neoproterozoic, Paleozoic, and Mesozoic granitoid magmatism in the Qinling Orogen, China: Constraints on orogenic process. *J. Asian Earth Sci.* **2013**, *72*, 129–151. [[CrossRef](#)]
44. Dong, Y.; Santosh, M. Tectonic architecture and multiple orogeny of the Qinling Orogenic Belt, Central China. *Gondwana Res.* **2016**, *29*, 1–40. [[CrossRef](#)]
45. Cheong, C.H. Stratigraphy and paleontology of the Late Paleozoic of Korea (1). *J. Korea Earth Sci. Edu. Soc.* **1979**, *1*, 3–16. (In Korean)
46. Chun, H.Y. Permo-Carboniferous plant fossils from the Samcheok coalfield, Gangweondo, Korea Part 1. *J. Paleontol. Soc. Korea* **1985**, *1*, 95–122.

47. Cleal, C.J.; Ziqiang, W. A new and diverse plant fossil assemblage from the upper Westphalian Benxi Formation, Shanxi, China, and its palaeofloristic significance. *Geol. Mag.* **2002**, *139*, 107–130. [\[CrossRef\]](#)
48. Wang, J. Late Paleozoic macrofloral assemblages from Weibei Coalfield, with reference to vegetational change through the Late Paleozoic Ice-age in the North China Block. *Int. J. Coal Geol.* **2010**, *83*, 292–317. [\[CrossRef\]](#)
49. Ma, S.; Meng, Q.; Wu, G.; Duan, L. Late Paleozoic exhumation of the Inner Mongolia Paleo-Uplift: Evidence from sedimentary records. *Acta Geol. Sin.* **2014**, *88*, 1771–1789. (In Chinese)
50. Vermeesch, P. On the visualisation of detrital age distributions. *Chem. Geol.* **2012**, *312–313*, 190–194. [\[CrossRef\]](#)
51. Lee, S.-R.; Cho, K.-O. Precambrian crustal evolution of the Korean Peninsula. *J. Petrol. Soc. Korea* **2012**, *21*, 89–112. (In Korean) [\[CrossRef\]](#)
52. Lee, Y.; Cho, M.; Yi, K. In situ U–Pb and Lu–Hf isotopic studies of zircons from the Sancheong–Hadong AMCG suite, Yeongnam Massif, Korea: Implications for the petrogenesis of ~1.86 Ga massif-type anorthosite. *J. Asian Earth Sci.* **2017**, *138*, 629–646. [\[CrossRef\]](#)
53. Choi, T.; Lee, Y.I.; Orihashi, Y. Crustal growth history of the Korean Peninsula: Constraints from detrital zircon ages in modern river sediments. *Geosci. Front.* **2016**, *7*, 707–714. [\[CrossRef\]](#)
54. Yang, J.; Gao, S.; Chen, C.; Tang, Y.; Yuan, H.; Gong, H.; Xie, S.; Wang, J. Episodic crustal growth of North China as revealed by U–Pb age and Hf isotopes of detrital zircons from modern rivers. *Geochim. Cosmochim. Acta* **2009**, *73*, 2660–2673. [\[CrossRef\]](#)
55. Cawood, P.A.; Hawkesworth, C.J.; Dhuime, B. Detrital zircon record and tectonic setting. *Geology* **2012**, *40*, 875–878. [\[CrossRef\]](#)
56. Kim, M.G.; Lee, Y.I. The stratigraphy and correlation of the upper Paleozoic Pyeongan Supergroup of southern Korean Peninsula—A review. *J. Geol. Soc. Korea* **2017**, *53*, 321–338, (in Korean with English abstract). [\[CrossRef\]](#)
57. Kaczmarek, M.A.; Müntener, O.; Rubatto, D. Trace element chemistry and U–Pb dating of zircons from oceanic gabbros and their relationship with whole rock composition (Lanzo, Italian Alps). *Contrib. Mineral. Petr.* **2008**, *155*, 295–312. [\[CrossRef\]](#)
58. Linnemann, U.; Ouzegane, K.; Drareni, A.; Hofmann, M.; Becker, S.; Gärtner, A.; Sagawe, A. Sands of West Gondwana: An archive of secular magmatism and plate interactions—A case study from the Cambro-Ordovician section of the Tassili Ouan Ahaggar (Algerian Sahara) using U–Pb–LA-ICP-MS detrital zircon ages. *Lithos* **2011**, *123*, 188–203. [\[CrossRef\]](#)
59. Wang, X.; Griffin, W.L.; Chen, J.; Huang, P.; Li, X. U and Th contents and Th/U ratios of zircon in felsic and mafic magmatic rocks: Improved zircon-melt distribution coefficients. *Acta Geol. Sin. Engl.* **2011**, *85*, 164–174.
60. Arakawa, Y. Rb–Sr ages of the gneiss and metamorphosed intrusive rocks of the Hida metamorphic belt in the Urushiyama area, Gifu Prefecture, central Japan. *J. Jap. Ass. Min. Petr. Econ. Geol.* **1984**, *79*, 431–442. [\[CrossRef\]](#)
61. Arakawa, Y.; Saito, Y.; Amakawa, H. Crustal development of the Hida belt, Japan: Evidence from Nd–Sr isotopic and chemical characteristics of igneous and metamorphic rocks. *Tectonophysics* **2000**, *328*, 183–204. [\[CrossRef\]](#)
62. Wakita, K. Geology and tectonics of Japanese islands: A review—The key to understanding the geology of Asia. *J. Asian Earth Sci.* **2013**, *72*, 75–87. [\[CrossRef\]](#)
63. Ehiro, M.; Tsujimori, T.; Tsukada, K.; Nuramkhan, M. Palaeozoic basement and associated cover. In *The Geology of Japan*; Moreno, T., Wallis, S., Kojima, T., Gibbons, W., Eds.; Geological Society of London: London, UK, 2016; pp. 25–60.
64. Kim, S.W.; Oh, C.W.; Choi, S.G.; Ryu, I.C.; Itaya, T. Ridge Subduction-Related Jurassic Plutonism in and around the Okcheon Metamorphic Belt, South Korea, and Implications for Northeast Asian Tectonics. *Int. Geol. Rev.* **2005**, *47*, 248–269. [\[CrossRef\]](#)
65. Choi, T.; Lee, Y.I. Thermal histories of Cretaceous basins in Korea: Implications for response of the East Asian continental margin to subduction of the Paleo-Pacific Plate. *Isl. Arc* **2011**, *20*, 371–385. [\[CrossRef\]](#)
66. Maruyama, S.; Isozaki, Y.; Kimura, G.; Terabayashi, M. Paleogeographic maps of the Japanese Islands: Plate tectonic synthesis from 750 Ma to the present. *Isl. Arc* **1997**, *6*, 121–142. [\[CrossRef\]](#)
67. Takahashi, Y.; Cho, D.-L.; Mao, J.; Zhao, X.; Yi, K. SHRIMP U–Pb zircon ages of the Hida metamorphic and plutonic rocks, Japan: Implications for late Paleozoic to Mesozoic tectonics around the Korean Peninsula. *Isl. Arc* **2018**, *27*, e12220. [\[CrossRef\]](#)

68. Isozaki, Y. Jurassic accretion tectonics of Japan. *Isl. Arc* **1997**, *6*, 25–51. [[CrossRef](#)]
69. Stampfli, G.M.; Hochard, C.; V  rard, C.; Wilhem, C. The formation of Pangea. *Tectonophysics* **2016**, *593*, 1–19. [[CrossRef](#)]
70. Lee, Y.I.; Lim, H.S.; Choi, T.; Orihashi, Y. Detrital zircon U–Pb ages of the late Paleozoic Sadong Formation in the Pyeongchang coalfield, Gangweon-do Province, Korea: Implications for depositional age and provenance. *J. Geol. Soc. Korea* **2010**, *46*, 73–81. (In Korean)
71. Kim, S.W.; Park, S.-I.; Jang, Y.; Kwon, S.; Kim, S.J.; Santosh, M. Tracking Paleozoic evolution of the South Korean Peninsula from detrital zircon records: Implications for the tectonic history of East Asia. *Gondwana Res.* **2017**, *50*, 195–215. [[CrossRef](#)]
72. Cope, T.; Ritts, B.D.; Darby, B.J.; Fildani, A.; Graham, S.A. Late Paleozoic Sedimentation on the Northern Margin of the North China Block: Implications for Regional Tectonics and Climate Change. *Int. Geol. Rev.* **2005**, *47*, 270–296. [[CrossRef](#)]
73. Lee, T.-H.; Park, K.-H.; Yi, K. Nature and evolution of the Cretaceous basins in the eastern margin of Eurasia: A case study of the Gyeongsang Basin, SE Korea. *J. Asian Earth Sci.* **2018**, *166*, 19–31. [[CrossRef](#)]
74. Wiedenbeck, M.; Hanchar, J.M.; Peck, W.H.; Sylvester, P.; Valley, J.; Whitehouse, M.; Kronz, A.; Morishita, Y.; Nasdala, L.; Fiebig, J.; et al. Further characterisation of the 91500 zircon crystal. *Geostand. Geoanal. Res.* **2004**, *28*, 9–39. [[CrossRef](#)]



   2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).