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Detrital Zircon LA-ICP-MS U-Pb Ages of the North Liaohe Group from the Lianshanguan Area, NE China: Implications for the Tectonic Evolution of the Paleoproterozoic Jiao-Liao-Ji Belt

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Abstract: The Liaohe Group, which is a significant lithostratigraphic unit within the Paleoproterozoic Jiao-Liao-Ji Belt situated between the Longgang and Liaonan-Nangrim blocks, comprises the Langzishan, Li'eryu, Gaojiayu, Dashiqiao, and Gaixian formations, which are characterized mainly by a clastic-rich sequence with an interlayered bimodal-volcanic sequence, carbonate-rich sequence, and (meta-)pelite-rich sequence. Currently, the tectonic background and evolution of the Liaohe Group remain contentious. Based on the study of detrital zircon geochronology and the zircon trace element characteristics in the Langzishan and Li'eryu formations in the North Liaohe Group in the Lianshanguan area, NE China, this paper reveals the formations' provenances, depositional ages, and relationships with Paleoproterozoic granitoids (the Liao-Ji granites). The present results, in conjunction with previous studies, indicate that the depositional age of the Langzishan Formation is 2136 Ma and that of the Li'eryu Formation is 1974 Ma. The provenances of the Langzishan Formation and the Li'eryu Formation are mainly characterized by Neoarchean-to-early-Paleoproterozoic basement rocks (~2.6–2.4 Ga) and the Liao-Ji granites (~2.2–2.0 Ga), respectively. Moreover, the coeval mafic and metasedimentary rocks of the Liaohe Group exhibit characteristics of an extensional environment, which is represented by the tectonic setting of a back-arc basin. Notably, the Upper Langzishan Formation records a prominent shift in sedimentary environment from a passive continental margin to an active continental margin. In terms of the tectonic evolution of the North Liaohe Group and the Jiao-Liao-Ji Belt, our proposed model suggests that the Archean basement rocks in the northern part of the continental block, along with a limited contribution from the Paleoproterozoic Liao-Ji granites, served as the primary sources for the Langzishan Formation. Subsequently, the rapid deposition of the Li'eryu Formation was influenced by intense magmatism and subsequent erosion of the subduction-related magmatic arc (the Liao-Ji granites) within a back-arc basin environment. Lastly, the deposition of clastic materials from the Longgang blocks and the Liao-Ji granites resulted in the formation of the Gaojiayu, Dashiqiao, and Gaixian formations.

Keywords: detrital zircon U-Pb ages; North Liaohe Group; provenance; Jiao-Liao-Ji Belt; North China Craton

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1. Introduction

The North China Craton (NCC) is one of the oldest cratons in the world and is bounded by the Late Paleozoic–Early Mesozoic Central Asian Orogenic Belt to the north, the Early Paleozoic–Mesozoic Qilian-Qingling-Dabie orogen to the southwest, and the

Mesozoic Sulu Orogen to the east (Figure 1a) [1–4]. Generally, the NCC is considered to have been formed by the Paleoproterozoic amalgamation (~1.85 Ga) of two distinct Archean-to-Paleoproterozoic blocks named the Eastern and Western blocks separated by the Trans-North China Orogen or Central Orogenic Belt [5–13]. Additionally, the Eastern and Western blocks are viewed as assemblies of several micro-blocks that collided to form the critical Paleoproterozoic orogenic belts, such as the Khondalite Belt (KB) and Jiao-Liao-Ji Belt (JLJB). However, the evolutionary histories of these micro-blocks are still highly controversial [5,10,14–16]. Therefore, recognizing the Paleoproterozoic orogenic belts is a significant achievement in understanding the history of the NCC.

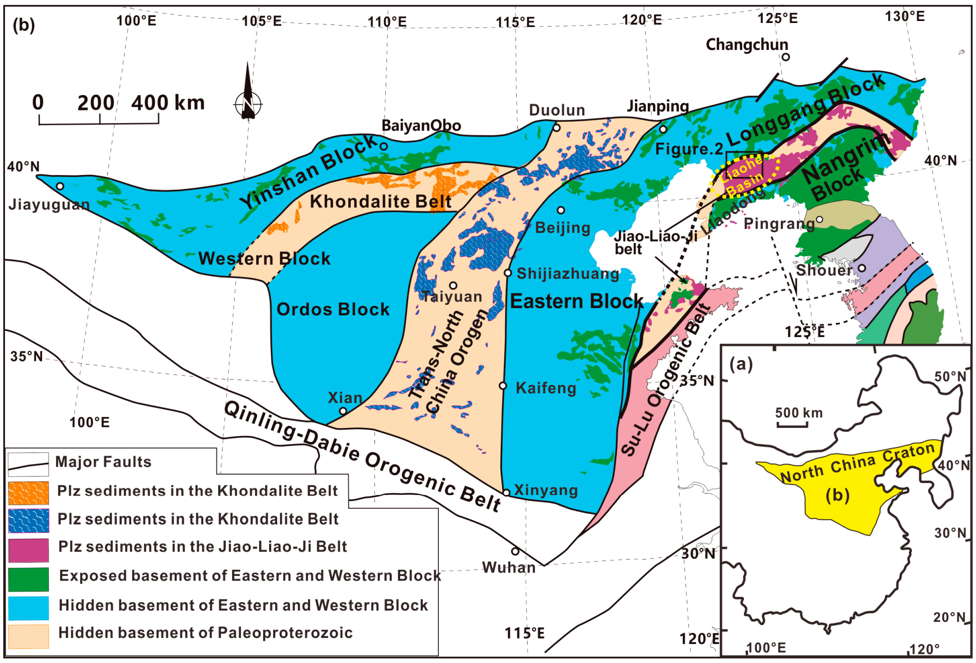

Figure 1. (**a**) Outline Map of Central and Eastern China. (**b**) Tectonic division of the North China Craton. (modified after Zhao et al., 2005 [10]).

Among the Paleoproterozoic orogenic belts in the NCC, the JLJB separates the Eastern Block into the Longgang Block (LB) in the northwest and the Liaonan-Nangrim Block (LNB) in the southeast. As previously reported, this belt records a long and extremely complex history of magmatism, multi-metamorphic evolution, tectonic deformation, and crustal overgrowth and reworking, but its origin and tectonic evolution remain controversial despite a large number of recent studies on the belt [17–27]. Possible explanations for the origin and evolution of the JLJB include: (a) the opening and closing of an intracontinental rift [20,28–32], (b) arc-continent collision [33–37], and (c) a combination of the two previous scenarios, with intracontinental rifting progressing to the formation of a new ocean basin or back-arc basin then being subsequently closed by subduction [13,27,38–40].

Zircon is a common accessory mineral in most of the detrital sedimentary rocks (especially sandstones) due to its stable crystal structure, and because of the high closure temperature of the U-Th-Pb isotope system, it remains stable from low to high metamorphism conditions and weathering transport. Therefore, detrital zircon U-Pb geochronology has been widely used to define the maximum sedimentary age of sedimentary strata [41] and trace the provenance of the sediments [42], significantly contributing to the understanding of early crustal tectono-thermal evolution [43].

The detrital zircons collected from meta-sedimentary rocks in the North and South Liaohe groups of the JLJB are significantly important and commonly studied. Previous research has determined the ages of clastic and metamorphic zircons in sedimentary rocks of the Liaohe Group, yielding age peaks of 2200–2000 Ma and ~2500 Ma and determining the sedimentary age of the metasedimentary rocks to be 2.0–1.9 Ga [44–46]. Although previous studies have examined the detrital zircons in these sedimentary rocks, discrepancies still exist in determining the sedimentary age of the Liaohe Group [36,44,45,47,48].

By conducting U-Pb dating of these zircons (15 samples with 17–74 valid data for each sample), this study aims to determine the provenances, maximum depositional ages, and depositional environments of the North Liaohe Group in the Langzishan area, NE China. Furthermore, by comparing the similarities and differences between the North and South Liaohe groups, this study will provide a more detailed understanding of the tectonic setting and evolution of the Liaohe Group, as well as of the JLJB.

2. Geological Setting

The JLJB is a Paleoproterozoic orogenic belt located in the northeastern part of the Eastern Block of the NCC. It extends from southern Jilin Province to eastern Shandong Province, tectonically separating the Precambrian Eastern Block into the LNB and the LB (Figure 1) [9,10,20]. The belt is primarily composed of greenschist to granulite facies-metamorphic sedimentary rocks and widespread granitoids, along with a small number of mafic intrusions and volcanic successions (Figure 1) [29,49].

2.1. Paleoproterozoic (Meta-)Volcanic-Sedimentary Sequences

According to the distribution of the Paleoproterozoic volcanic-sedimentary sequence, the JLJB can be divided into two sub-belts: the northern sub-belt, comprising the Laoling Group in southern Jilin, the North Liaohe Group in eastern Liaoning, and the Fenzishan Group, and the southern sub-belt, including the Ji'an, South Liaohe, and Jingshan groups and possibly the Macheonryeong Group in North Korea [10,12,27,28]. These successions are transitional, starting from a basal clastic-rich sequence and lower bimodal-volcanic sequence, going through a middle carbonate-rich sequence, and ending with an upper pelite-rich sequence [50].

In the Liaodong peninsula, the Liaohe Group comprises a thick sequence of metamorphosed volcanic-sedimentary rocks. In the northern part of the Liaohe Group, the lithology mainly consists of clastic and carbonate rocks, while in the southern part, it is predominantly composed of a volcanic-clastic-carbonate succession. These two groups are separated by faults defined by the locations of the Gaixian-Ximucheng-Taziling-Jiangcaodianzi-Aiyang areas [28,32,51].

Traditionally, the Liaohe Group has been divided into five formations from bottom to top: the Langzishan, Li'eryu, Gaojiayu, Dashiqiao, and Gaixian formations. It is noteworthy that the lowermost Langzishan Fm. is only distributed in the North Liaohe Group, while the Gaixian Fm. is mostly found in the South Liaohe Group [28,52].

2.2. Paleoproterozoic Magmatism

The Paleoproterozoic granites are widely exposed in the JLJB and are mainly divided into two sequences in the Liaodong Peninsula: the Liao-Ji granites and rapakivis [53]. The Liao-Ji granites are mostly distributed in the southern part, with zircon U-Pb ages ranging from 1.93 Ga to 2.30 Ga. Based on their main mineral assemblages (quartz, plagioclase, perthite, biotite, and, in some cases, amphibole, magnetite, or tourmaline) and geochemical affinities, the Liao-Ji granites are classified into magnetite monzonitic granites (I-type Liao-Ji granite) [38,39,54–56] and amphibole monzonitic granites (A-type Liao-Ji granite) [20,57,58]. According to Liu et al. [59], the Liao-Ji granites resulted from the partial melting of the Archean basement rocks, and their gneissic structures have been attributed to syn-emplacement deformation. However, Qu et al. [60] and Chen et al. [61] argued that the foliation of the Liao-Ji granites resulted from post-emplacement deformation, and that the granites belonged to migmatites derived from both crustal and mantle sources.

The rapakivi granites are mostly distributed in the eastern part of the JLJB, with zircon U-Pb ages ranging from 1.8 Ga to 1.9 Ga. They are generally composed of quartz, microcline, garnet, and biotite, which are their major mineral assemblages [17,60,62,63]. The genesis of the rapakivi granites in the JLJB has been interpreted differently. For instance, Li et al. [38]

suggested that they resulted from the detachment of the orogenic belt or the upwelling of mantle magma, while Chen et al. [61] proposed that they were post-orogenic granites, a mixture of magmas from both crustal and mantle sources. Yang et al. [54] believed that the rapakivi granites in the Shuangcha area were formed in 1890 ± 21 Ma, marking the end of the orogenic processes of the JLJB.

2.3. Geology of the Study Area

The study area is situated in the Lianshanguan region of eastern Liaoning Province (Figure 2), which is characterized by the widespread exposure of the Archean basement and Paleoproterozoic strata, including the North Liaohe Group, a minor amount of Neoarchean supracrustal rocks (Anshan Group in Anshan-Benxi Area Liaoning), Paleoproterozoic igneous rocks, and Phanerozoic strata (Figures 2 and 3) [64–66].

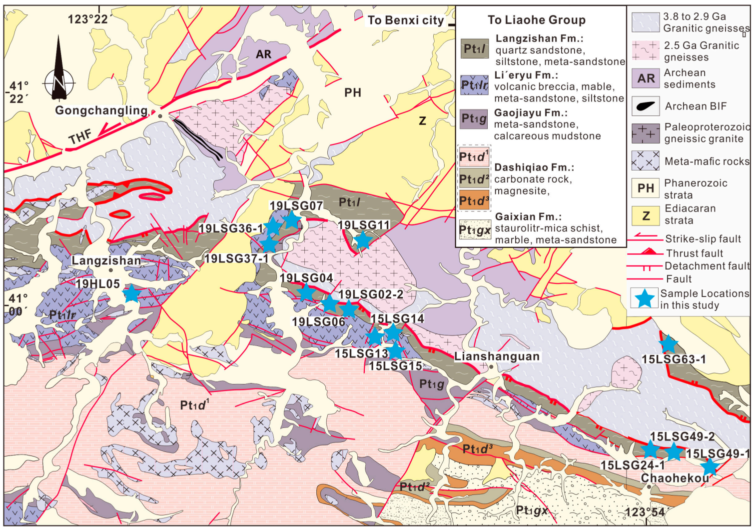

Figure 2. Stratigraphic structural map of the Lianshanguan area, NE China, showing the detailed sampling locations. (Modified from Wen et al., 2021 [67]).

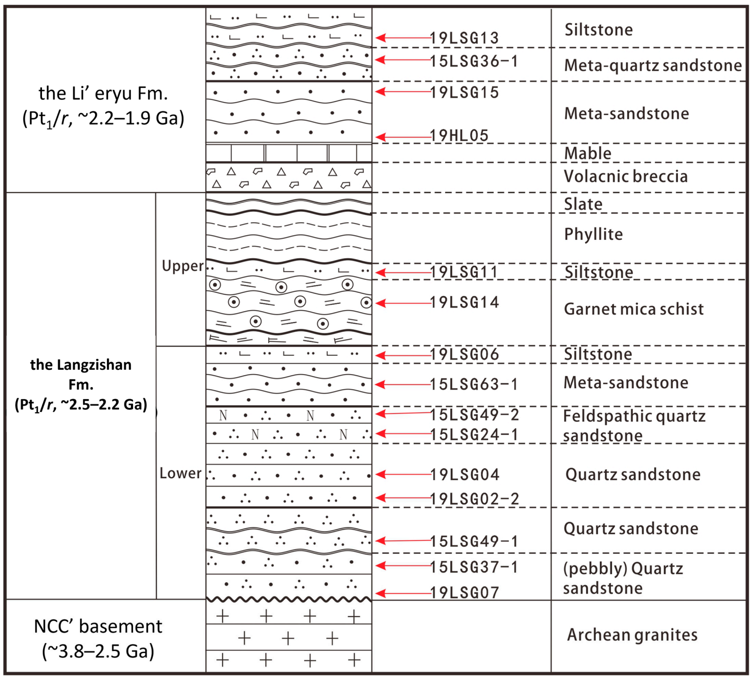

Figure 3. Stratigraphic histogram of sampling sites.

The Archean basement in the Lianshanguan area, mainly consisting of granitic gneisses and migmatites, forms a short-axis, anticline-like dome that stretches approximately 40 km in the NW direction and has a width of 5–10 km [68]. The outer edge of the dome is overlain by the North Liaohe Group and Sinian strata, and an unconformity separates it from the overlying Langzishan Fm., resulting in the formation of a typical weathering paleocrust, particularly in the Sandaoling area. In addition, numerous quartz veins have been developed in the granitic basement and truncated by the unconformity surface (Figure 4a). The granitic conglomerate sandstone—located above—and a medium-sized sandy conglomerate are present. A large-scale ductile shear zone has been developed on the southern edge of the dome (Figure 4b–d). Based on kinematic indicators including asymmetric folds, rotated boudins, and offset markers, the ductile zone shows a dextral shearing sense. The Paleoproterozoic igneous rocks here consist of both deformed felsic granites and mafic rocks with ages ranging from approximately 2.2 to 1.9 Ga [24,51,69,70].

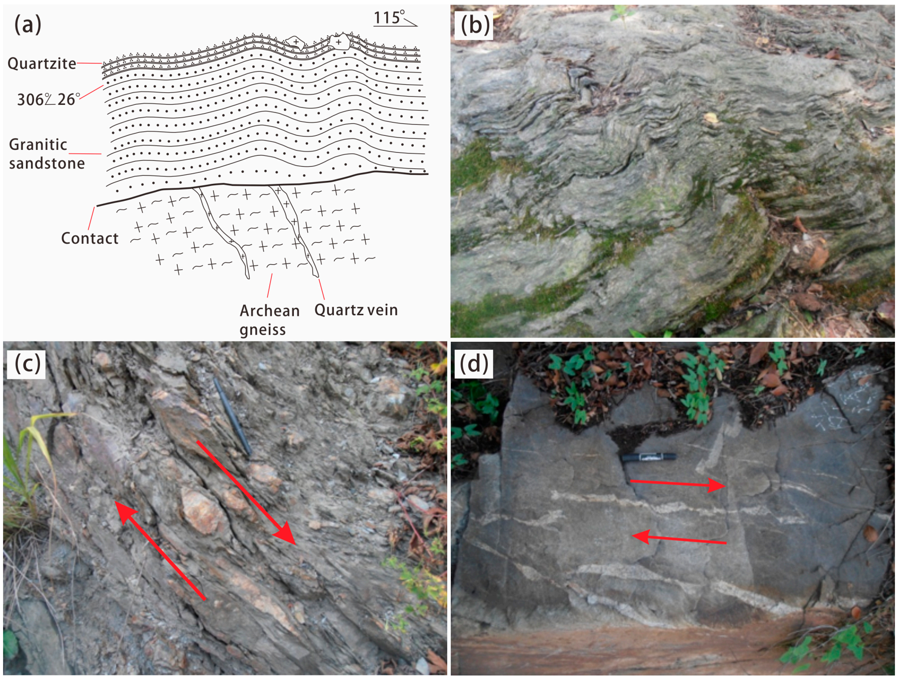

Figure 4. Unconformity contact relationship between the Langzishan Fm. and Lianshanguan granite (basement). Red arrows represent the shearing directions. (**a**) Sketch of unconformity interface. (**b**) Fold deformation of the Langzishan Fm. (**c**) Mica schist and cataclastic quartz schist. (**d**) Dextral sheared schist and granitic vein of the Langzishan Fm.

The Langzishan Fm. (Pt_1l), the lowermost unit of the North Liaohe Group, primarily comprises garnet-bearing kyanite-cordierite-mica schists, mica-quartz schists, two mica schists, and quartzites with coarse sandstone and conglomerate at the base (Figure 3). Calcite marbles, tremolite-dolomite marbles, phosphates, and uranium deposits are also present within the formation. The formation is unconformably in contact with the Neoarchean basement of the LB. The Li'eryu Fm. (Pt_1lr) is characterized by boron-bearing (meta-)volcanic rocks and clastic sedimentary series, including meta-rhyolitic and mafic volcanics, sandstones, and marbles at the base, and meta-sandstones and tremolite (dolomite) marbles above. The presence of numerous volcanic rocks with arc-affinity suggests intense magmatic activity near subduction zones and magmatic arcs [71]. The Gaojiayu Fm. (Pt_1g) is defined by carbonaceous clastic and clay rocks with minor volcanics [72,73]. It consists mainly of garnet-bearing mica schists, biotite leptynites, and diopside-dolomite marbles with minor rhyolitic and mafic volcanics at the base. The Dashiqiao Fm. (Pt_1d) is represented by carbonate rocks with minor clastic rocks, comprising dolomitic or calcic marbles in its lower and upper sections and mica schists in its middle section. The Gaixian Fm.

(Pt_1gx) is a meta-pelitic sequence primarily composed of staurolite-garnet-mica schists, sillimanite-mica schists, mica leptynites, and phyllites with thin marble layers.

3. Petrographic Description

The (meta-)sedimentary rocks in the Langzishan and Li'eryu formations from the North Liaohe Group were chosen for detrital zircon LA-ICP-MS U-Pb dating, and these included (pebbly) quartz sandstones (19LSG07, 15LSG37-1, 15LSG49-1, 19LSG02-2, and 19LSG04), feldspathic quartz sandstones (15LSG24-1 and 15LSG49-2), meta-sandstone (15LSG63-1), siltstones (19LSG06 and 19LSG11), and garnet mica schist (19LSG14) from the Langzishan Fm. Furthermore, the meta-sandstones (19HL05-2 and 19LSG15), siltstone (19LSG13), and quartz sandstone (15LSG36-01) from the Li'eryu Fm. were also included (Figures 2 and 3). The petrographic features of representative samples are outlined below (Only representative surface samples have been selected for detailed description, and all sample descriptions are available within the Supplementary Materials).

3.1. Representative Samples from the Langzishan Fm

Samples 19LSG07 and 15LSG37-1 were obtained from the granitic conglomerate weathering paleocrust located at the contact zone between the Langzishan Fm. and the Lianshanguan granitic rock mass (basement). These pebbly sandstones exhibit a massive structure and are composed of well-sorted, subangular clastic particles. Specifically, the samples contain ~10% quartz, ~35% microcline feldspar, ~25% plagioclase feldspar, and ~25% lithic fragments, along with a small amount of chlorite and amphibole. Siliceous cementation is observed, with both inlaid cementation and particle support being evident (Figure 5a,b).

Sample 19LSG02-2 is a quartz sandstone, with the clastic particles mainly consisting of quartz (93%), alkali feldspar (5%), and a small quantity of impurities (2%). Alkali feldspar is mostly microcline with gridiron twining (Figure 5c).

Sample 19LSG04 is a terrigenous quartz sandstone, primarily composed of quartz (~90%), with small amounts of alkaline feldspar (8%), dark minerals (2%), and micas (Figure 5d).

Sample 19LSG06 is a calcareous siltstone consisting mainly of quartz (~90%), with minor feldspar (8%) and lithic fragments (2%). A thin calcite vein with severe alteration is present, and the cement is calcareous, shows contact cementation, and is particle-supported (Figure 5e).

Lastly, sample 19LSG14 is a garnet-mica schist with a porphyroblastic texture, and the minerals in it mainly consist of biotite (~30%), quartz (45%), and feldspar (20%) with a small quantity of garnet (~5%). The grain size of the garnet phenocryst is up to 2.0 cm in diameter (Figure 5f).

3.2. Representative Samples from the Li'eryu Fm

Sample 19LSG15 is a meta-sandstone, characterized by a mineral assemblage of quartz (43%), alkaline feldspar (25%), calcite (15%), biotite (10%), muscovite (5%), and a small proportion of dark minerals (2%). The rock's cement is calcareous, with contact cementation and particle support being observed (Figure 5g).

Sample 19LSG13 is a siltstone, exhibiting a silty structure. The clastic particles are mainly composed of quartz (75%), feldspar (18%), and muscovite (5%), with a small proportion of dark minerals (2%). The rock is well-sorted, with contact cementation and particle support evident (Figure 5h).

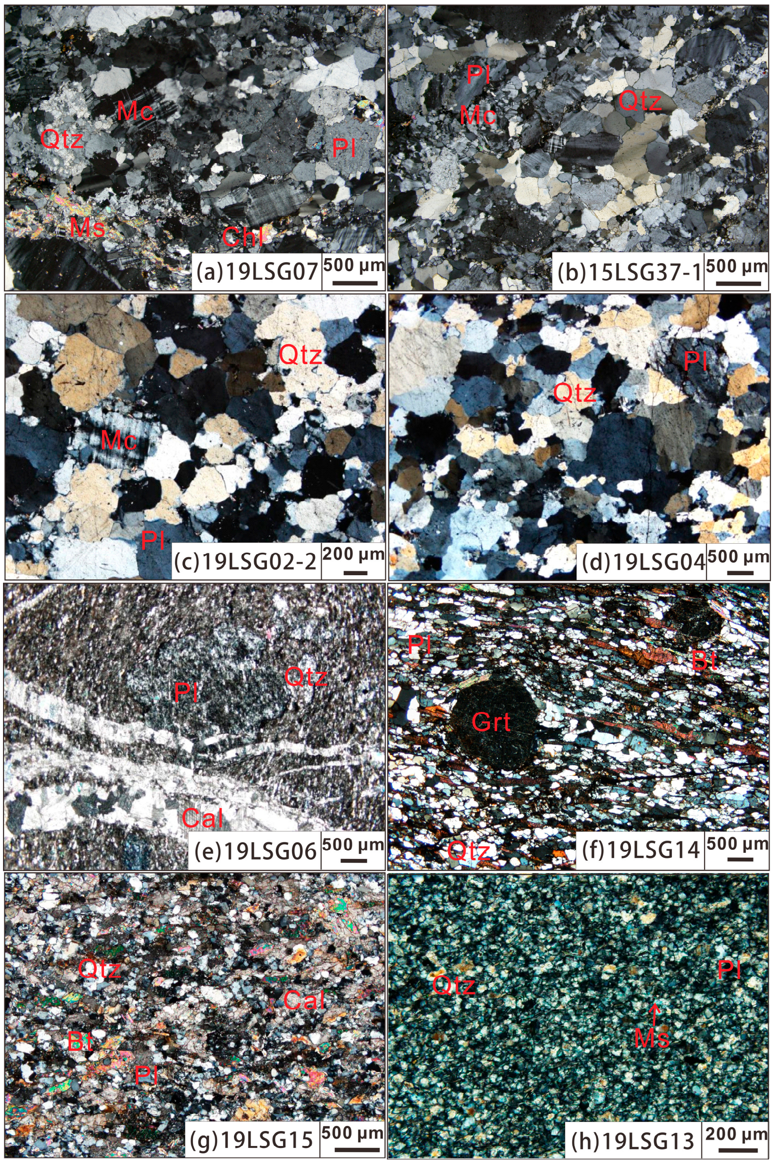

Figure 5. Representative thin-section micrographs of the Langzishan formation and the Li'leyu formation of the North Liaohe Group. Image (**a**) is from the sample 19LSG07 (quartz sandstone), (**b**) is from the sample 15LSG37-1 (quartz sandstone), (**c**) is from the sample 19LSG02-2 (quartz sandstone), (**d**) is from the sample 19LSG04 (quartz sandstone), (**e**) is from the sample 19LSG06 (siltstone), (**f**) is from the sample 19LSG14 (garnet mica schist), (**g**) is from the sample 19LSG15 (meta-sandstone), and (**h**) is from the sample 19LSG13 (siltstone). The abbreviations for the minerals are as follows: Qtz—quartz, Mc—microcline, Pl—plagioclase, Ms—muscovite, Chl—chlorite, Cal—calcite, Grt—garnet, and Bt—biotite.

4. Zircon U-Pb LA-ICP-MS Dating

4.1. Analytical Techniques

Zircon grains were separated using the conventional magnetic separation technique and hand picking methods at Yuneng Mineral Separation Company in Hebei Province. The separated zircon particles were fixed with epoxy resin and polished until the cores were exposed, and then coated with carbon. Prior to the determination of the sample, the sample surface was cleaned with 3% HNO3 to remove the C-coating. Transmitted light, reflected light, and cathodoluminescent (CL) image acquisitions (Figure 6) were conducted at the Beijing Gaonianlinghang Corporation. LA-ICP-MS U-Pb zircon dating was performed at the Key Laboratory of Mineral Resources Evaluation in Northeast Asia, Ministry of Land and Resources, Jilin University, Changchun, China. CL image phase formation was obtained using the Momo CL3+ cathodoluminescent device produced by the company Gatan, which is based in the UK. Zircon dating was conducted using the latest generation Agilent 7900 ICP-MS with a shield torch from the company Agilent. The laser ablation system comprised the ComPex102 Excimerlaser (working material ArF, wavelength 193 nm) from Lambdaphysik company in Germany and an optical system from the company Microlas. Helium was used as the carrier gas for the ablation material, and the spot beam diameter was 32 μm. The frequency was 10 Hz, the laser energy was 90 mJ, the gas background acquisition time of each analysis point was 20 s, and the signal acquisition time was 40 s. Zircon 91500 was used as an external standard for age calibration, and NIST SRM610 silicate glass was applied for instrument optimization. The test procedures and lead correction methods have previously been specified in the literature [74]. In order to minimize the effects of common lead loss in ancient zircon (dated to >1000 Ma), $^{207}Pb/^{206}Pb$ age was used, and $^{206}Pb/^{238}U$ age was used for Zircon dated to <1000 Ma [75]. The error quoted for isotope ratios and ages (i.e., standard error) was 1σ. The GLITTER (ver. 4.4, Macquarie University, Balaclava Rd, Macquarie Park NSW 2109) and Isoplot (Ver. 4.15) [76] programs were used for data processing, age calculations, and concordia plots. The analytical data can be found in Supplementary Table S1.

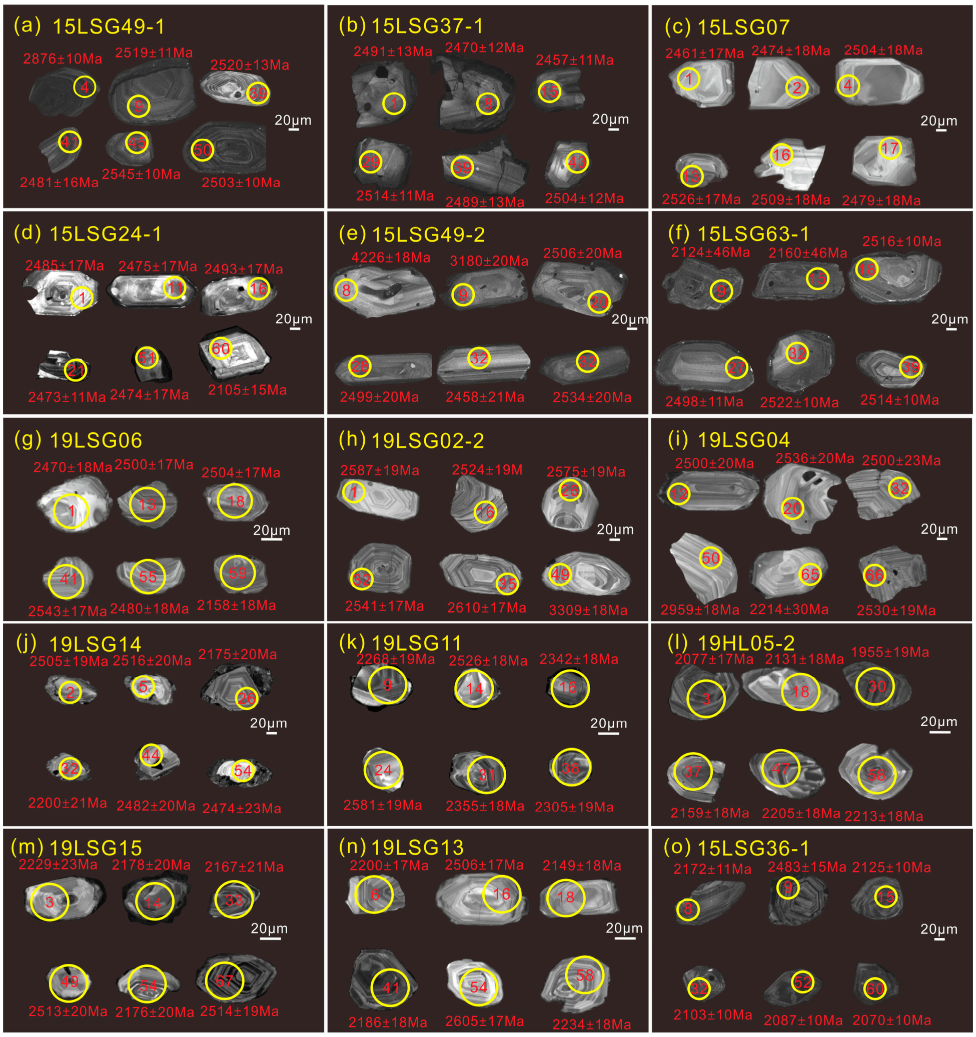

Figure 6. (**a**–**c**) Representative CL images of zircon from sedimentary rocks in Lower Langzishan Fm., (**d**–**k**) representative CL images of zircon from sedimentary rocks in Upper Langzishan Fm., (**l**–**o**) representative CL images of zircon from sedimentary rocks in Li'eryu Fm. Yellow circles indicate the experimental positions.

4.2. Results of the Detrital Zircon U-Pb LA-ICP-MS Ages

Due to the large number of samples, many of those displaying similar features and data in the main text are only briefly grouped and described. For detailed descriptions of individual samples, please refer to the Supplementary Materials.

In the Lower Langzishan Fm., a total of 520 zircons were analyzed (Supplementary Table S1), and these showed oscillatory zonings with Th/U ratios ranging from 0.17 to 4.17, indicating that they are typical magmatic zircons. Zircon grains from the quartz sandstone (15LSG49-1) in the bottom layer of the Langzishan Fm. were analyzed. Out of the 60 zircons analyzed, 50 yielded the ^{207}Pb/^{206}Pb age of 2433–2736 Ma, with an age peak at 2538 $\pm$ 13 Ma (Figures 6a and 7a). Zircon grains from pebbly quartz sandstones (15LSG37-1 and 19LSG07) from the Langzishan Fm. showed concordant data, with the ^{207}Pb/^{206}Pb ages ranging from 2190 to 3031 Ma and having an age peak at 2508 $\pm$ 17 Ma (Figure 6b,c and Figure 7b,c). Zircon grains from feldspathic quartz sandstones (15LSG24-1 and 15LSG49-2) had ^{207}Pb/^{206}Pb ages ranging from 2105 to 2564 Ma and 2368 to 2678 Ma, with age peaks at 2465 $\pm$ 16 Ma and 2525 $\pm$ 14 Ma, respectively (Figure 6d,e and Figure 7d,e). Zircon grains from metamorphic sandstone (15LSG63-1) showed the ^{207}Pb/^{206}Pb age range of 2457–2713 Ma, with a weighted average age of 2488 $\pm$ 13 Ma (Figures 6f and 7f). The siltstone (19LSG06) sample showed ^{207}Pb/^{206}Pb ages ranging from 2378 to 2622 Ma, with an age peak at 2516 $\pm$ 8.2 Ma (Figures 6g and 7g). Zircon grains from quartz sandstone (19LSG02-2 and 19LSG04) had the ^{207}Pb/^{206}Pb ages ranging from 2446 to 2747 Ma, with an age peak at 2563 $\pm$ 14 Ma (Figure 6h,i and Figure 7h,i).

A garnet mica schist (sample 19LSG14) and a siltstone (sample 19LSG11) were collected from the Upper Langzishan Fm., and the zircon grains from the schist showed ^{207}Pb/^{206}Pb ages ranging from 1945 to 2671 Ma, with a main age peak at 2505 $\pm$ 19 Ma and a secondary peak at 2185 $\pm$ 36 Ma (Figures 6j and 7j). Zircon grains from siltstone showed ^{207}Pb/^{206}Pb ages ranging from 2117 to 2581 Ma, with an age peak at 2341 $\pm$ 53 Ma (Figures 6k and 7k).

In the Li'eryu Fm., the analysis of zircon grains extracted from different samples of metamorphic sandstone (19HL05, 19LSG15, 15LSG36-1) and siltstone (19LSG13) was conducted. The zircon grains were found to have short columnar or rounded morphology, with aspect ratios less than 2:1, and exhibited oscillatory zoning with Th/U ratios ranging from 0.11 to 1.20, indicating that they were typical magmatic zircons. The ^{207}Pb/^{206}Pb age of these zircon grains ranged from 1846 to 2270 Ma with age peaks at different times depending on the samples. The analysis also revealed older ages for some of the samples, ranging from 2479 to 2605 Ma (Figures 6i–o and 7i–o).

In summary, eleven samples from the Langzishan Fm. and four samples from the Li'eryu Fm. were systematically studied by using the detrital zircon LA-IC-MS U-Pb dating. A total of 709 effective data from a total of 894 analyses were chosen (90% < concordance < 110%) for further U-Pb age probability plots (Figure 8) and a discussion of the geological implications. Among them, the U-Pb age ranges of 433 zircons in the (pebbly) quartz sandstones, and the feldspathic quartz sandstones from the Lower Langzishan Fm., were 2105–4226 Ma, with the main age peak being at 2462 Ma. Besides, there were only 14 data distributed in the period 2105–2265 Ma (peak at ~2195 Ma) and 6 older data distributed in the period 2938–3309 Ma, barring one sample dated to 4226 Ma (Figure 8a). Going upward in the stratigraphic sequence, 75 valid data on the garnet mica schist in the Upper Langzishan Fm. were distributed from 1945 Ma to 2671 Ma, with the main peak being at 2458 Ma and a remarkable secondary peak being at 2179 Ma (Figure 8b). Moreover, 203 effective data (1846–2605 Ma) in the Li'eryu Fm. showed the main age peak being at 2160 Ma (Figure 8c). Only 1 younger age—1846 Ma (Th/U ratio 0.08)—was present, significantly indicating the range of metamorphic ages within the formation. Besides this, very few zircon grains discovered in the Li'eryu Fm. yielded U-Pb ages of 2506–2501 Ma (n = 3).

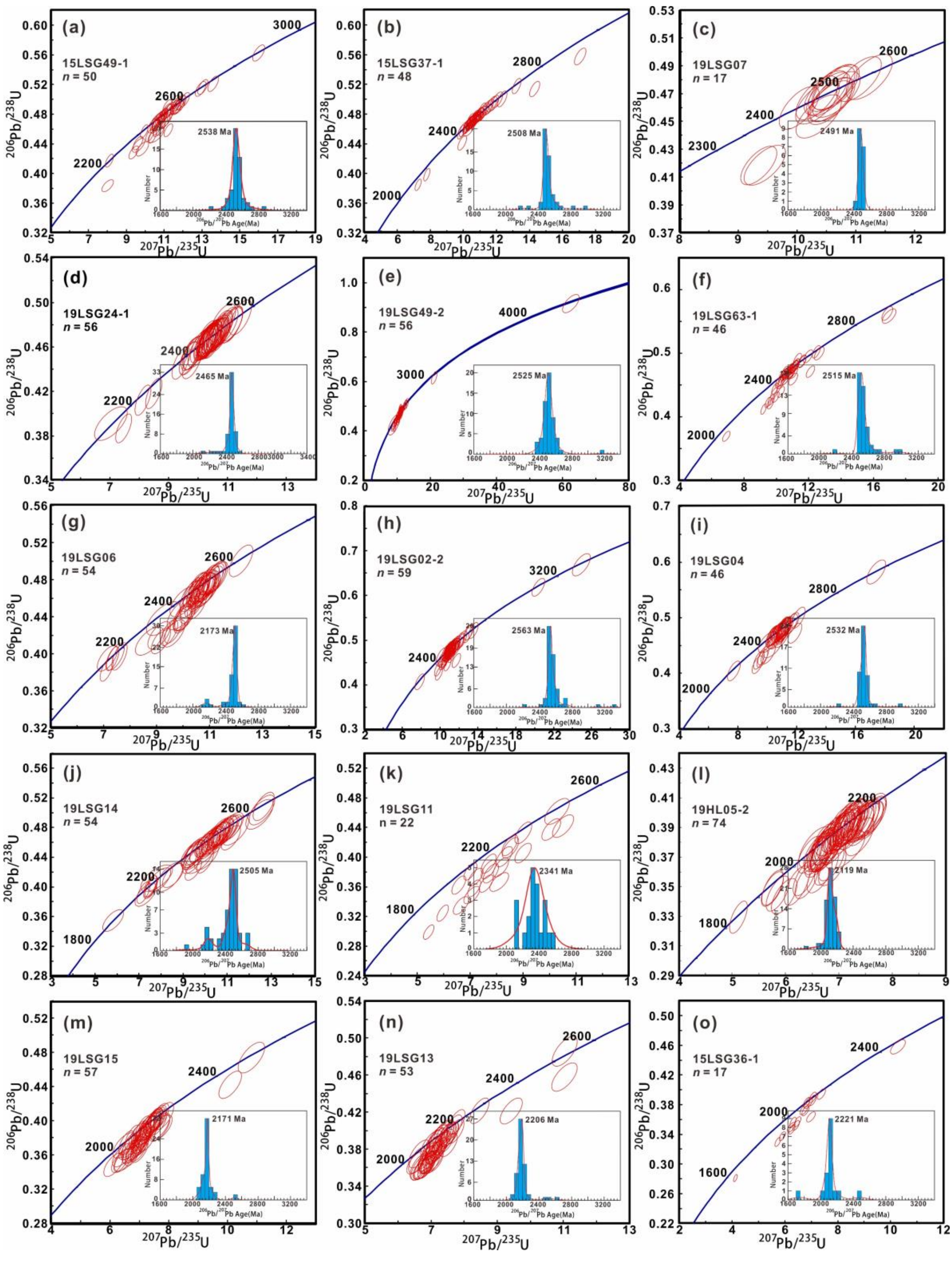

Figure 7. 206Pb/ 235U vs. 207Pb/ 238U diagrams and U-Pb age histograms (sub-figure) for the U-Pb detrital zircon analyses of sedimentary rocks from the Lower Langzishan Fm. (**a**–**c**), the Upper Langzishan Fm. (**d**–**k**) and the Li'eryu Fm. (**l**–**o**) of the North Liaohe Group.

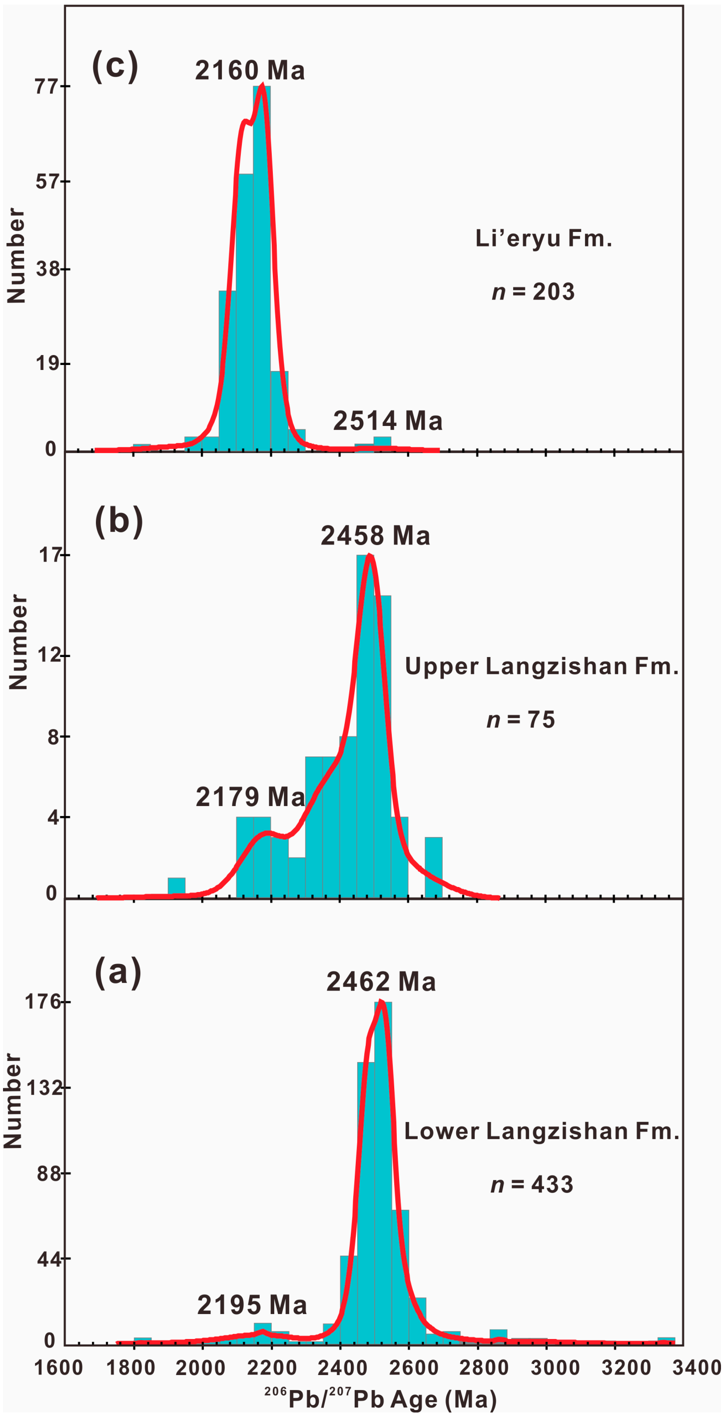

Figure 8. (**a**) U-Pb ages histograms of detrital zircons from metasedimentary rocks within the Lower Langzishan Fm., (**b**) U-Pb ages histograms of detrital zircons from metasedimentary rocks within the Upper Langzishan Fm., (**c**) U-Pb ages histograms of detrital zircons from metasedimentary rocks within the Li'eryu Fm.

5. Discussion

5.1. Provenance Analysis

The Langzishan and Li'eryu formations are characterized by two distinct age peaks, with ages of approximately 2.5 Ga and 2.2 Ga, respectively. Granitoids dated to ~2.5 Ga are widely developed, and represent the ages of the crystallized basement of the NCC [28,35,44,77–85]. The proportion of zircons aged ~2.2 Ga increases significantly in the upper layer of the Langzishan and Li'eryu formations, a finding that is consistent with what has been noted in a large number of 2.1–2.2 Ga magmatic rocks (the Liao-Ji granites) developed in the JLJB [20,24,25,35,37–39,48,56,86–89]. This result is in agreement with the results obtained by Liu et al. [90] from the dating of aluminum-rich metamorphic sedimentary rocks in the Liaohe Group (the main peak age is 2.05–2.15 Ga, and the secondary peak age is 2.45–2.55 Ga). The provenance of the Li'eryu Fm. has primarily been derived from the Liao-Ji granites, as determined through the analysis of peak ages and Lu-Hf isotopes, in a manner consistent with that of previous studies [44,83]. Although some detrital zircon U-Pb ages fall within the 2.8–3.3 Ga range, much like the ages of Eoarchean and middle Archean zircons found in the Anshan-Benxi area of NE China [91–93], no clastic zircons dating earlier than 3300 Ma have been identified. This suggests that unlike what happened in the Anshan-Benxi area, Eoarchean granites were not exhumed and deposited in the Langzishan Fm. in the Lianshanguan area.

Significantly, a few detrital zircons in the Langzishan Fm. have ages ranging from 2650 Ma to 2800 Ma, with a peak age of 2680 Ma (Figure 7b–d). Regional magmatism that is consistent with these ages is rare in the area and adjacent areas. This indicates two possibilities. The first is that the magmatic rocks of approximately 2680 Ma in the Langzishan Fm. and its adjacent areas have undergone weathering and removal during later tectonic thermal events. Secondly, recent discoveries have shown that some Neoarchean granites in the Anshan-Benxi area contain circa 2.7 Ga-inherited zircons and a small number of clastic zircons with an age of 2680 Ma, possibly originating from inherited zircons in the Neoarchean granites in the Benxi area [64]. Furthermore, only one older age—of approximately 4.2 Ga—is present, a finding which may be consistent with Hadean zircons documented in the eastern NCC [94,95], although the geological significance of these zircons is still unclear.

The detrital zircons provide a means of examining the sources of sediments, as their trace element compositions can be analyzed (Figure 9) [96]. The detrital zircons analyzed in the study showed a positive correlation between U and Y concentrations, suggesting derivation from acidic or intermediate acidic igneous rocks such as granite, syenite, and pegmatite. A few zircons from throughout the stratigraphy fall within the field of mafic rocks (Figure 9a,b). The Eu/Eu* distribution range (0.1–1) is more concentrated than that of Ce/Ce* (1–100) in the zircons from the study area, suggesting derivation from granites, nepheline-syenite pegmatites, and pegmatites. The Y concentrations and Yb/Sm display a linear distribution (Figure 9c), suggesting derivation from intermediate-silicic igneous plutons, such as granite, syenite pegmatites, and larvikites, with some zircons derived from mafic rocks. The positive correlation between the Nb and Ta concentrations of these zircons (Figure 9d) suggests derivation from granites, syenites, and mafic rocks, while a few zircons may have originated from carbonatites. Overall, Figure 9 suggests a common derivation for these zircons from intermediate-silicic igneous plutons. The felsic Archean basement of the NCC and the Paleoproterozoic Liao-Ji granites in the JLJB are likely provenances for the Langzishan Fm. and Li'eryu Fm., respectively.

Zircon trace element compositions can provide valuable insights into magmatic, metamorphic, and crustal processes and settings [96–98]. We used U/Yb versus Hf and Y diagrams to constrain their tectonic environments. The detrital zircons from both the Langzishan Fm. and the Li'eryu Fm. display similar characteristics when continental and oceanic crustal fields are plotted in, suggesting that they were derived from continental or mixed sources (Figure 10a,b). Additionally, some concordant detrital zircons have been plotted in the arc-related/orogenic fields in the Th/U-versus-Nb/Hf and Th/Nb-versus-Hf/Th diagrams, while a few zircons have been plotted in the within-plate/anorogenic field (Figure 10c,d).

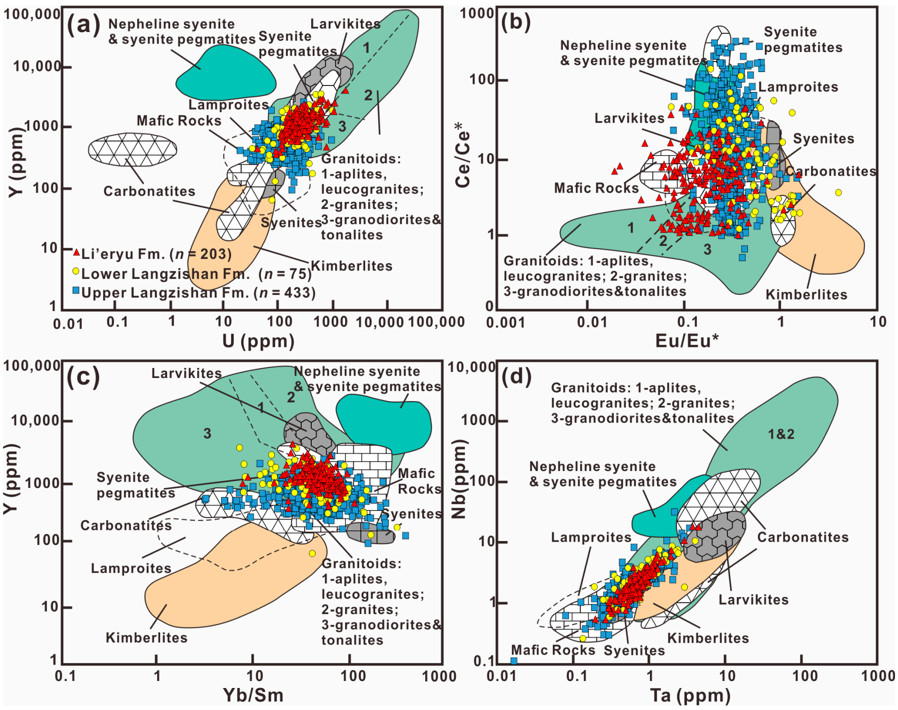

Figure 9. Zircon Y versus U (**a**), Ce/Ce* versus Eu/Eu* (**b**), Y versus Yb/Sm (**c**), and Nb versus Ta (**d**), with the images showing different compositions of zircons derived from different rock types (Belousova et al., 2002 [96]).

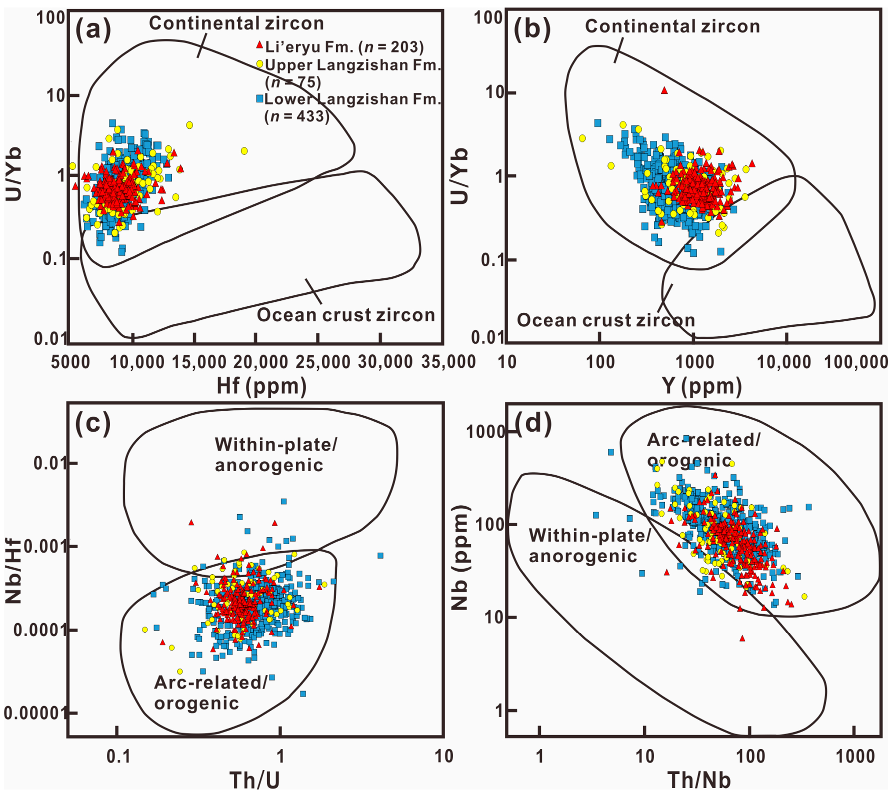

Figure 10. (**a**,**b**) Zircon Hf and Y versus U/Yb (Grimes et al., 2007 [98]), (**c**) Th/U versus Nb/Hf (Yang et al., 2012 [99]), and (**d**) Th/Nb versus Hf/Th (Yang et al., 2012 [99]).

In summary, it was found in this study that the detrital zircons in the study area were mainly derived from intermediate-silicic igneous rocks and formed in a tectonic setting of continental or mixed-continental-and-oceanic fields with arc-related/orogenic characteristics.

5.2. Depositional Age of the Langzishan and Li'eryu Formations

Due to the absence of volcanic rocks or pyroclastic components in the Langzishan Fm., its depositional age has long been a matter of debate. Some scholars argue that it formed between 2.05–1.93 Ga [12,44,48,84], while Xu et al. [27] propose an earlier depositional age of prior to 2.17 Ga. Based on zircon geochronology of aluminum-rich schist gneiss in the South and North Liaohe formations, Liu et al. [44] obtained an important age of ca. 1.95 Ga for the oldest metamorphic zircons in the Langzishan Fm. For the Li'eryu Fm., Wang et al. [88] reported a maximum depositional age from the South Liaohe Group based on the representative youngest individual zircon U-Pb ages of 2050 Ma. Furthermore, Xu et al. [27] compared the age distributions of detrital zircons and concluded that the deposition time of the Li'eryu Fm. was between 2.17–2.10 Ga. However, Chen et al. [100] concluded a geochronological study on acid volcanic rocks in the Liaoyang area and believed that there were three periods of magmatic activity in the Li'eryu Fm., i.e., 2190–2180 Ma, 2110–2100 Ma, and 1970–1960 Ma. Therefore, the previous deposition time of 2.05–2.1 Ga may represent the second period of Li'eryu Fm. magmatic activity, while the latest phase of magmatic activity should have been 1.95 Ga.

Over the past two decades, three methods have been commonly used to determine the depositional ages of sediments based on the youngest age populations in the detrital zircons. These methods include (1) using the age of the youngest detrital zircon as an older limit on deposition [101], (2) determining the peak ages of the youngest detrital zircons to represent the maximum age of the sedimentary rocks [101], and (3) calculating the weighted average ages of the three youngest detrital zircons [102]. For this study, we considered the primary detrital zircon data using the youngest age as the basis for examining the depositional age. Using Kernel Density Estimation (KDE) [103], the minimum crystallization age was found to be around 2113 $\pm$ 23 Ma (n = 3), indicating that the maximum depositional age of the Langzishan Fm. could not be earlier than 2136 Ma within 95% confidence. For the Li'eryu Fm., 203 valid data on detrital zircons were examined, and two ages of 1955 $\pm$ 19 Ma in primary magmatic zircons were identified in sample 19HL05. It was therefore concluded that there was a probability that the deposition time of the Li'eryu Fm. could not be earlier than 1974 Ma within 95% confidence. This finding is consistent with the results of previous studies based on the ages of interlayered volcanic rocks (~1.95 Ga) in the Li'eryu Fm. [100].

In summary, previous studies suggest an upper limit depositional age of ~1.95 Ga for the Liaohe Group, and based on the formation time of Liao-Ji granites (2.1–2.2 Ga), which are considered the primary sedimentary sources of the Liaohe Group, we propose a depositional age of 2.20–1.95 Ga for the Paleoproterozoic Liaohe Group. We also propose depositional time limits of ~2100 Ma for the Langzishan Fm. and ~1950 Ma for the Li'eryu Fm. based on our own experimental data. However, the sedimentary time limit of other strata has not been established in this study due to the lack of our own experimental data. Nonetheless, according to Wang et al. [88], the maximum depositional ages for the Gaojiayu, Dashiqiao, and Gaixian formations from the South Liaohe Group are 2069 Ma, 2043 Ma, and 1915 Ma, respectively, based on the representative youngest individual zircon U-Pb ages.

5.3. Sedimentary Similarities and Differences between the North and South Liaohe Groups

Luo et al. [44] proposed that the North and South Liaohe Groups formed simultaneously due to their similar provenances, based on a comparison of the U-Pb and Hf isotopic compositions of detrital zircons. In this study we combined our own findings with previous research to reveal differences in the sedimentary sequence and age distribution of detrital zircons in each formation of the Liaohe Group (Figure 11). For example, the South Liaohe Group has limited records on the Langzishan Fm., and there are virtually no records of the

Gaixian Fm. in the North Liaohe Group [19–21,40]. The Langzishan Fm. is only present in the North Liaohe Group, which could indicate two possibilities: it may not have been discovered in the South Liaohe Group, or it may have only been deposited in the northern margin of the LB during the Paleoproterozoic era [28,52]. Considering all the previous reports, we propose that the differences among the strata in the North and South Liaohe Groups could provide insights and evidence for the tectonic and evolutionary model of the Liaohe Group. This study collected a total of 5380 effective detrital zircon data, including 1232 data from the Langzishan Fm., 1159 data from the Li'eryu Fm., 1107 data from the Gaojiayu Fm., 642 data from the Dashiqiao Fm., and 1240 data from the Gaixian Fm. See Figure 11 for details on the geochronological data, which were grouped according to their exact locations for each formation.

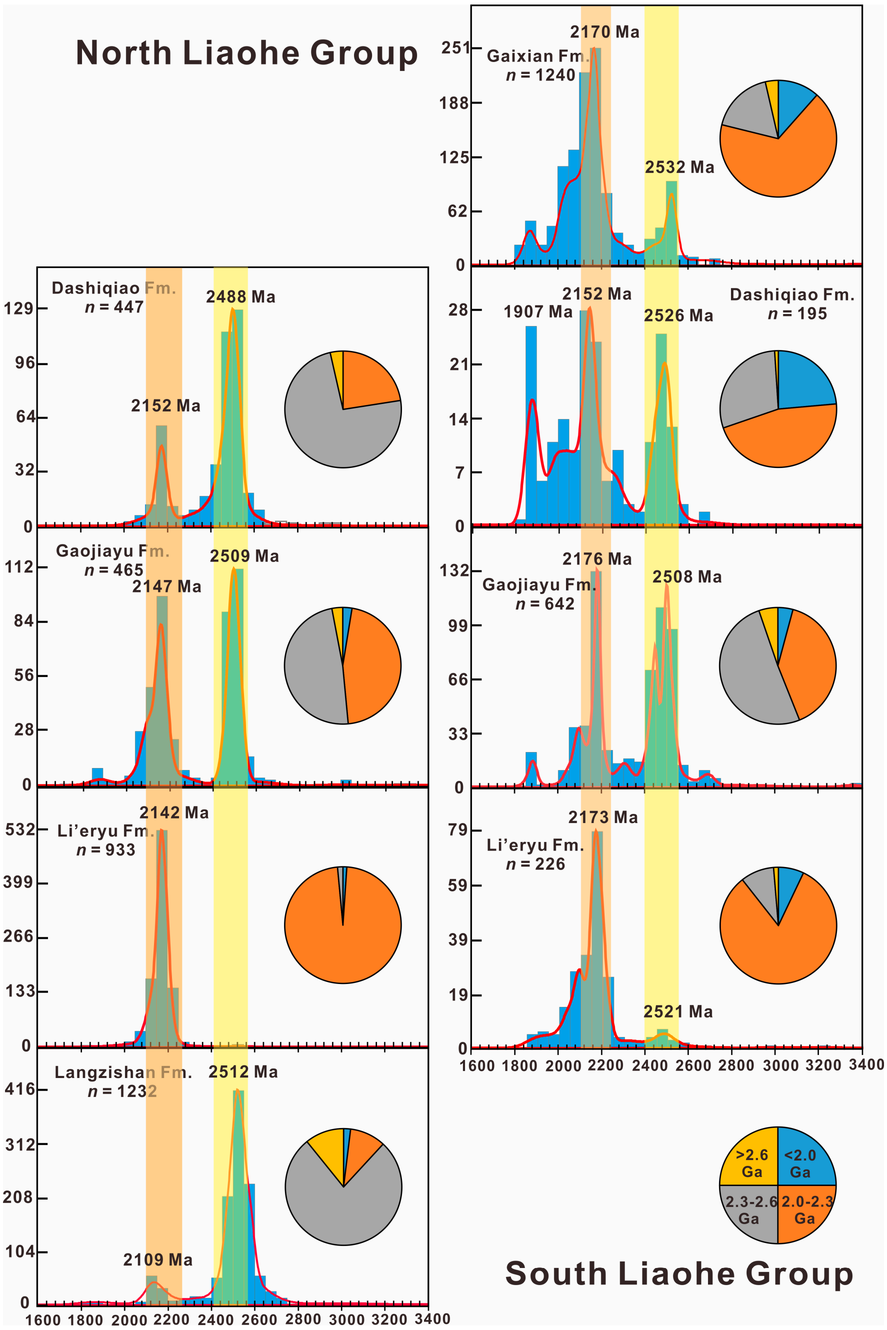

Figure 11. Collected U-Pb age distributions for the detrital zircons from (meta-)sedimentary rocks within the Liaohe Group (part of the data was collected from [28,35,44,52,83,104–113]).

Compared to what has been noted in other formations in the Liaohe Group, only the lower layers of the Langzishan Fm. contain detrital zircon ages from the Eoarchean to middle Archean eras, with a much higher proportion of Neoarchean (~2.5 Ga) ages than in other formations (Figure 11). Additionally, the Li'eryu Fm. has a relatively unimodal peak age (at ~2150 Ma) barring a few Archean ages (~2.52 Ga) that appear in the southern part. The detrital zircon ages show bimodal peaks at ~2.49–2.53 Ga and ~2.15–2.18 Ga for the Gaojiayu, Dashiqiao, and Gaixian formations. However, the Dashiqiao and Gaixian formations from the South Liaohe Group both have a younger secondary peak of ~1.91 Ga, which likely represents the metamorphic ages of these formations [114–116].

Figure 11 serves as a critical transitional record revealing that detrital zircon from the basement of the NCC vanishes in the Li'eryu Fm. (~2.5 Ga) but reappears in the upper strata. One possible explanation for the single peak age (~2.18–2.15 Ga) in the Li'eryu Fm. is based on the deposition of a substantial number of magmatic zircons (~2.2 Ga) from arc-related magmas (the Liao-Ji granites) [20,24,37,48,95,117,118]. During this period, intense magmatic activity accompanied the expansion and rapid deposition of a back-arc basin [37,48,95,116], possibly leading to the formation of a single age of provenance in the Li'eryu Fm. However, magmatic activity weakened during the deposition of the Gaojiayu, Dashiqiao, and Gaixian formations, indicating that the back-arc basin may have started to shrink. Consequently, the detrital zircon age distribution of these formations exhibits two peak ages originating from the Archean NCC basement (~2.5 Ga) and Paleoproterozoic Liao-Ji granites (~2.2 Ga).

It is worth noting that the detrital zircon ages from the Li'eryu Fm. of the South Liaohe Group exhibit two age peaks, i.e., the main peak of ~2.17 Ga and a secondary peak of ~2.52 Ga. In contrast, the age distribution from the Li'eryu Fm. in the North Liaohe Group has only a single peak of ~2.14 Ga (Figure 9). This significant difference in the age spectra suggests that the clastic materials in the Li'eryu Fm. have not been derived from the source area in the LB to the north, which lacks the records of the ~2.5 Ga Archean basement. This implies that the provenance of the Li'eryu Fm. may have been from the south. Moreover, the unimodal age spectra in the Li'eryu Fm. suggest a single provenance of ~2.1–2.2 Ga arc-affinity magmatites that were rapidly uplifted to the surface, likely forming a geomorphic feature that was high in the south and low in the north. The small amounts of clastics of ~2.5 Ga in age may be remnants of the ancient NCC's basement that are preserved in the magmatic arcs to the south. This finding, which further suggests that the Li'eryu Fm. might have undergone rapid deposition, is consistent with the hypothesis proposed by Wang et al. [104].

Furthermore, the correlation between the clastic zircon crystallization age (CA) and the sedimentary age of the host rock (DA) can constrain the tectonic environments of sedimentary rocks, based on differences in zircon formation and storage capacity in various tectonic settings [119]. Data from this study and from previous investigations of the Langzishan and Li'eryu formations were incorporated into the $^{206}Pb/^{207}Pb$ age map based on the accumulation ratio, which yielded depositional ages of 2136 Ma and 1974 Ma for the Langzishan and Li'eryu formations, respectively. As shown in Figure 12, the Lower Langzishan Fm. was represented by eight samples displaying CA-CD > 150 Ma at 5% of the zircon populations, indicating their deposition in a passive continental margin under extensional tectonic settings [119]. The Upper Langzishan Fm. was characterized by two samples showing CA-DA < 150 Ma at 5% of the zircon populations, and most of the data fell within the convergent basin. When combined with the age distribution characteristics of detrital zircons in the lower and upper layers of the Langzishan Fm., the results suggest that the sedimentary process of the Langzishan Fm. represents the transformation from a passive to an active continental margin. In contrast, all the samples from the Li'eryu Fm. showed CA-DA < 150 Ma at 5% of the zircon populations, and the main samples fell within the convergent basin, indicating that they were deposited on an active continental margin. This result is consistent with previous research results [27,109,113].

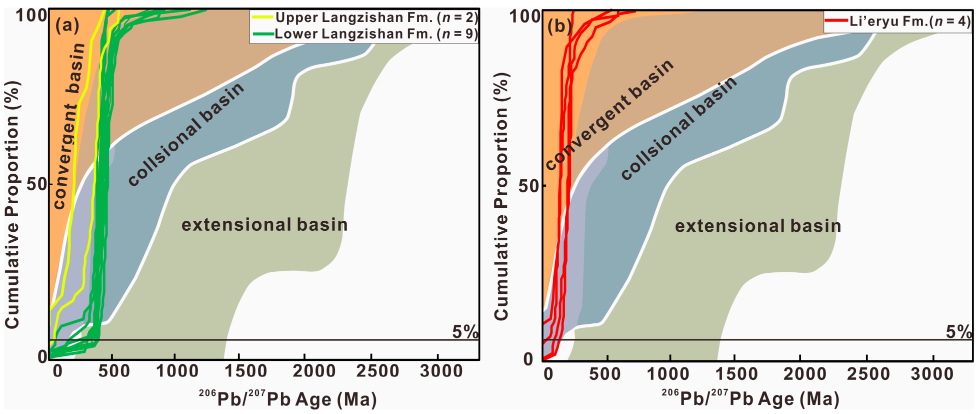

Figure 12. Detrital zircon ages vs. cumulative proportion diagrams for original basin settings of the Langzishan Fm. (**a**) and the Li'eryu Fm. (**b**) (Cawood et al., 2012 [119]).

5.4. Geological Significance and Sedimentary Background

As mentioned earlier, the tectonic evolution of the JLJB has been the subject of much debate, with three models proposed: (1) intra-continental rift opening and closure, (2) arc-continent collision, and (3) back-arc basin expansion and subsequent convergence [13,20,27–29,31–40,56]. Recently, models (2) and (3) have gained more support [27,30,36,37,40] despite ongoing controversy. The active continental margin tectonic model, first proposed by Bai et al. [33], posits that the LB and LNB represent two exotic blocks while the JLJB is an intervening island arc or back-arc basin. This viewpoint has been supported by various pieces of evidence, including: (1) studies of Paleoproterozoic Liao-Ji granites using geochronology and geochemistry, which revealed that the I- and A2-type ~2.2–2.0 Ga granites constituted a calc-alkaline series likely formed in the extensional tectonic setting of a continental arc [52,54,55,120] and/or back-arc basin [27,38,90,106,121–123]; (2) the reinterpretation of previously regarded (meta-)mafic rocks, which were believed to be examples of bimodal magmatism, together with the meta-volcanic rocks and Liao-Ji granites, that were developed in a rift environment as typical island arc basalts formed in a back-arc tectonic setting [15,24,68,124]; and (3) newly obtained detrital zircon U-Pb ages, combined with previous studies [27,104], showing unimodal age peaks of ~2.5 Ga for the Langzishan Fm. and ~2.15 Ga for the Li'eryu Fm., and bimodal age peaks at ~2.51 Ga and ~2.17 Ga for the Gaojiayu and Dashiqiao formations, respectively. Notably, these varying zircon age spectra are difficult to interpret in the context of intra-continental rift opening, particularly for the deposition of the Li'eryu Fm. In addition, the age patterns (ages vs. cumulative proportion; Figure 12) suggest that the depositional tectonic environment was a passive continental margin for the Langzishan Fm. and an active continental margin, interpreted as a back-arc basin environment [104], for the Li'eryu Fm.

In summary, based on a combination of previous findings and our own new results, the present tectonic scenario is more consistent with initial back-arc extension along an active continental margin followed by arc-continent collision for the Paleoproterozoic JLJB. We propose a rough evolutionary model (Figure 13) that encapsulates the following statements. (a) During the period of ca. > 2.2 Ga, the southeastern margin of the LB was a passive continental margin, especially during the depositional period for the Lower Langzishan Fm. The basement rocks of the LB to the north were the primary sources for the deposition of the Lower Langzishan Fm. (Figure 13a). (b) Subsequently, in ~2.2 Ga, oceanic subduction began beneath the southeastern margin of the LB, leading to the formation of arc-affinity magmatic rocks (the Liao-Ji granites). As a result, the depositional environment transformed into an active continental margin, and a small amount of subduction-related monzogranite gneiss (~2.2 Ga Liao-Ji granite) likely contributed to the clastics in the Upper Langzishan Fm. (Figure 13b). (c) With the continuous subduction of the oceanic crust, it is possible that an increasing subduction rate or angle of the oceanic plate led to vertical slab roll-back and the contemporaneous extension of the active continental margin [125]. In around 2.2–2.0 Ga, a back-arc basin was initially formed. Accompanied by lithospheric extension and mantle upwelling, the partial melting of ancient crustal material, together with minor contributions of juvenile mafic rocks, generated widespread A2-type granitoids in the JLJB [27,54,55,90,120–123]. During this time, a large volume of volcanic clastics (boron-bearing), and debris derived from the magmatic arc, were rapidly deposited, forming the Li'eryu Fm. in around 1.95 Ga (Figure 13c). Importantly, the single peak of the detrital zircon age spectrum probably indicates intensive subduction activity during the deposition of the Li'eryu Fm. After that, the Gaojiayu, Dashiqiao, and Gaixian formations were extensively deposited in the back-arc basin. The provenance from the LB gradually increased, supplying ancient (~2.5 Ga) basement materials together with clastics from the magmatic arc (~2.2–2.0 Ga Liao-Ji granites), possibly because the subduction became relatively slow or the back-arc basin began to shrink. Finally, in around 1.87–1.85 Ga [10,20,27,90], the back-arc basin was closed and formed the JLJB.

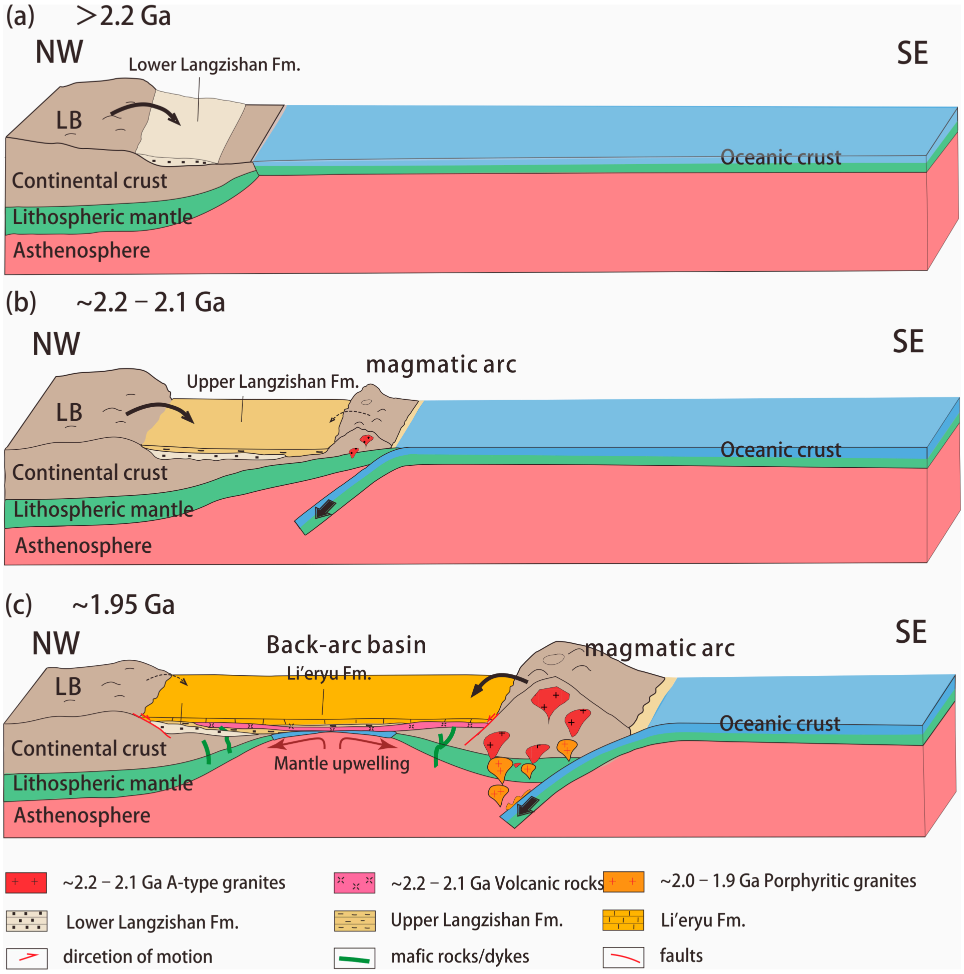

Figure 13. Schematic diagram of structural evolution of Liaohe Group. For the provenances of the Langzishan and Li'eryu formations, the ~3.3–2.5 Ga clastic materials in the sedimentary rocks of the lower Langzishan Fm. came from the erosion of the LB's basement on the NW side (**a**), minor amounts of ~2.2–2.1 Ga clastic materials of the upper Langzishan Fm. were derived from the erosion of a small amount of ~2.2–2.1 Ga granite on the SE-direction (**b**), and a large amount of 2.2–2.1 Ga clastic materials in the Li'eryu Fm. came mainly from the erosion of ~2.2–2.0 Ga Liao-Ji granites in the magmatic arc on the SE side (**c**).

6. Conclusions

Our study on zircon U-Pb geochronology and the trace element characteristics of sedimentary rocks from the Langzishan and Li'eryu formations of the North Liaohe Group of the JLJB of NCC allows us to add key constraints to the evolution of the Paleoproterozoic tectonics of the NCC. These include the following:

1. The depositional ages of the Langzishan Fm. and Li'eryu Fm. of the North Liaohe Group are 2136 Ma and 1976 Ma, respectively. The main provenances for these two formations are the Neoarchean basement rocks of the NCC (~2.6–2.4 Ga) and the Liao-ji granites (~2.2–2.0 Ga), respectively.
2. The sedimentary characteristics and geochronological evidence suggest that the depositional environment changed from a passive continental margin to an active continental margin during the deposition of the Upper Langzishan Fm.
3. The North and South Liaohe Groups exhibit similar sedimentary characteristics; however, some differences exist between the two, possibly due to variations in the local tectonic settings during deposition.
4. The North Liaohe Group was primarily supplied with clastic materials from the Archean basement rocks of the LB and a small amount of Paleoproterozoic Liao-Ji granites, which deposited the Langzishan Fm. The Li'eryu Fm. was rapidly deposited, likely due to intense magmatism and the erosion of the subduction-related magmatic arc (the Liao-Ji granites) in a back-arc basin environment. Finally, clastic materials from both the LB and Liao-Ji granites accumulated to form the Gaojiayu, Dashiqiao, and Gaixian formations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/min13050708/s1, Figure S1: Supplementary thin-section micrographs of the Langzishan Fm. and the Li'eryu Fm. in the North; Table S1: Results of LA-ICP-MS U-Pb zircon dating for the Langzishan and the Li'eryu formatios from the North Liaohe Group in the JLJB.

Author Contributions: J.G.: Methodology, Formal analysis, Writing—Original Draft; W.L. (Corresponding author): Supervision, Conceptualization, Writing—Review & Editing; Y.L.: Supervision, Conceptualization; Y.Z.: Data Curation, Formal analysis; T.L.: Investigation; Q.W.: Data Curation. All authors have read and agreed to the published version of the manuscript.

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References

1. Sengör, A.M.C.; Natal'in, B.A.; Burtman, U.S. Evolution of the Altaid tectonic collage and Paleozoic crustal growth in Eurasia. *Nature* **1993**, *364*, 209–304. [CrossRef]
2. Xu, J.W.; Zhu, G. Tectonic models of the Tan-Lu fault zone, eastern China. *Geol. Rev.* **1994**, *36*, 771–784.
3. Windley, B.F.; Alexeiev, D.; Xiao, W.; Kröner, A.; Badarch, G. Tectonic models for accretion of the Central Asian Orogenic Belt. *J. Geol. Soc. Lond.* **2007**, *164*, 31–47. [CrossRef]
4. Xiao, W.; Li, S.Z.; Santosh, M.; Jahn, B.-M. Orogenic Belts in Central Asia: Correlations and connections. *J. Asian Earth Sci.* **2012**, *49*, 1–6. [CrossRef]
5. Santosh, M.; Liu, D.; Shi, Y.; Liu, S.J. Paleoproterozoic accretionary orogenesis in the North China Craton: A SHRIMP zircon study. *Precambrian Res.* **2012**, *227*, 29–54. [CrossRef]
6. Wilde, S.A.; Zhao, G.C.; Sun, M. Development of the North China Craton during the Late Archaean and its final amalgamation at 1.8Ga; some speculations on its position within a global Palaeoproterozoic Supercontinent. *Gondwana Res.* **2002**, *5*, 85–94. [CrossRef]
7. Wilde, S.A.; Cawood, P.A.; Wang, K.Y.; Nemchin, A.A. Granitoid evolution in the Late Archean Wutai Complex. North China Craton. *J. Asian Earth Sci.* **2005**, *24*, 597–613. [CrossRef]

8. Zhao, G.C.; Wilde, S.A.; Cawood, P.A.; Lu, L.Z. Thermal evolution of Archean basement rocks from the eastern part of the North China Craton and its bearing on tectonic setting. *Int. Geol. Rev.* **1998**, *40*, 706–721. [CrossRef]
9. Zhao, G.C.; Wilde, S.A.; Cawood, P.A.; Sun, M. Archean blocks and their boundaries in the North China Craton: Lithological, geochemical, structural and P-T path constraints and tectonic evolution. *Precambrian Res.* **2001**, *107*, 45–73. [CrossRef]
10. Zhao, G.C.; Sun, M.; Wilde, S.A.; Li, S. Late Archean to Paleoproterozoic evolution of the North China Craton: Key issues revisited. *Precambrian Res.* **2005**, *136*, 177–202. [CrossRef]
11. Zhao, G.C.; Cawood, P.A.; Li, S.Z.; Wilde, S.A.; Sun, M.; Zhang, J.; He, Y.H.; Yin, C.Q. Amalgamation of the North China Craton: Key issues and discussion. *Precambrian Res.* **2012**, *222–223*, 55–76. [CrossRef]
12. Zhao, G.C.; Cawood, P.A. Precambrian Geology of China. *Precambrian Res.* **2012**, *222–223*, 13–54. [CrossRef]
13. Zhao, G.C.; Zhai, M. Lithotectonic elements of Precambrian basement in the North China Craton: Review and tectonic implications. *Gondwana Res.* **2013**, *23*, 1207–1240. [CrossRef]
14. Kusky, T.; Li, J.; Santosh, M. The Paleoproterozoic North Hebei Orogen: North China craton's collisional suture with the Columbia supercontinent. *Gondwana Res.* **2007**, *12*, 4–28. [CrossRef]
15. Xu, W.; Liu, F.; Santosh, M.; Liu, P.; Tian, Z.; Dong, Y. Constraints of mafic rocks on a Paleoproterozoic back-arc in the Jiao-Liao-Ji belt, North China craton. *J. Asian Earth Sci.* **2018**, *166*, 195–209. [CrossRef]
16. Zhai, M.G.; Santosh, M. The early Precambrian odyssey of the North China Craton: A synoptic overview. *Gondwana Res.* **2011**, *20*, 6–25. [CrossRef]
17. Zhao, Y.; Zhang, P.; Li, Y.; Li, D.T.; Chen, J.; Bi, W.Z. Geochemistry of two types of Palaeoproterozoic granites, and zircon U–Pb dating, and Lu–Hf isotopic characteristics in the Kuandian area within the Jiao-Liao-Ji Belt: Implications for regional tectonic setting. *Acta Geol. Sin.* **2020**, *55*, 7564–7580. [CrossRef]
18. Kim, J.; Cho, M. Low-pressure metamorphism and leucogranite magmatism, north-eastern Yeongnam Massif. Korea: Implication for Paleopreoterozoic crustal evolution. *Precambrian Res.* **2003**, *122*, 235–251. [CrossRef]
19. Lee, B.C.; Oh, C.W.; Cho, D.L.; Yi, K. Paleoproterozoic (2.0–1.97 Ga) subduction related magmatism on the north–central margin of the Yeongnam Massif, Korean Peninsula, and its tectonic implications for reconstruction of the Columbia supercontinent. *Gondwana Res.* **2019**, *72*, 34–53. [CrossRef]
20. Li, S.Z.; Zhao, G.C. SHRIMP U-Pb zircon geochronology of the Liao-ji granitoids: 4, 397-403. Constraints on the evolution of the Paleoproterozoic Jiao-Liao-Ji belt in the Eastern block of the North China Craton. *Precambrian Res.* **2007**, *158*, 1–16. [CrossRef]
21. Liu, D.Y.; Nutman, A.P.; Compston, W.; Wu, J.S.; Shen, Q.H. Remnants of 3800 crust in the Chinese part of the Sino-Korean craton. *Geology* **1992**, *20*, 339–342. [CrossRef]
22. Liu, Y.; Li, S. Paleoproterozoic granite in Haicheng-Dashiqiao-Jidong area, Eastern Liaoning. *Liaoning Geol.* **1996**, *1*, 10–18.
23. Hu, G.W. The basic structural characteristics of the early Proterozoic Liaohe Group. *Bull. Tianjin Inst. Geol. Miner. Resour.* **1992**, *26*, 179–188, (In Chinese with English Abstract).
24. Meng, E.; Liu, F.L.; Liu, P.H.; Liu, C.H.; Yang, H.; Wang, F.; Shi, J.R.; Cai, J. Petrogenesis and tectonic significance of Paleoproterozoic meta-mafic rocks from central Liaodong Peninsula, northeast China: Evidence from zircon U-Pb dating and in situ Lu-Hf isotopes, and whole-rock geochemistry. *Precambrian Res.* **2014**, *247*, 92–109. [CrossRef]
25. Sun, M.; Armstrong, R.L.; Lambert, R.S.; Jiang, C.C.; Wu, J.H. Petrochemistry and Sr, Pb and Nd isotopic geochemistry of Palaeoproterozoic Kuandian Complex, the eastern Liaoning Province, China. *Precambrian Res.* **1993**, *62*, 171–190.
26. Wang, C.W.; Liu, Y.J.; Li, D.T. New evidences on the correlation of Liaohe Lithogroup between the southern and the northern regions in eastern Liaoning Province. *J. Chang. Univ. Sci. Technol.* **1997**, *1*, 17–24, (In Chinese with English Abstract).
27. Xu, W.; Liu, F.L. Geochronological and geochemical insights into the tectonic evolution of the Paleoproterozoic Jiao-Liao-Ji Belt, Sino-Korean Craton. *Earth Sci. Rev.* **2019**, *193*, 162–198. [CrossRef]
28. Li, S.Z.; Zhao, G.C.; Sun, M.; Han, Z.Z.; Hao, D.F.; Luo, Y.; Xia, X.P. Deformation history of the Paleoproterozoic Liaohe Group in the Eastern Block of the North China Craton. *J. Asian Earth Sci.* **2005**, *24*, 659–674. [CrossRef]
29. Li, S.Z.; Zhao, G.C.; Sun, M.; Han, Z.Z.; Zhao, G.T.; Hao, D.F. Are the South and North Liaohe Groups different exotic terranes Sm–Nd isotope constraints on the Jiao-Liao-Ji orogen. *Gondwana Res.* **2006**, *9*, 198–208. [CrossRef]
30. Li, S.Z.; Zhao, G.C.; Santosh, M.; Liu, X.; Dai, L.; Suo, Y.H.; Tam, P.K.; Song, M.; Wang, P.C. Paleoproterozoic structural evolution of the southern segment of the Jiao-Liao-Ji belt, North China Craton. *Precambr. Res.* **2012**, *200–203*, 59–73. [CrossRef]
31. Peng, Q.M.; Palmer, M.R. The Paleoproterozoic boron deposits in eastern Liaoning, China—a metamorphosed evaporite. *Precambrian Res.* **1995**, *72*, 185–197. [CrossRef]
32. Zhang, Q.; Yang, Z. *Early Crust and Mineral Deposits of Liaodong Peninsula*; Geological Publishing House: Beijing, China, 1988; (In Chinese with English Abstract).
33. Bai, J. *The Precambrian Geology and Pb-Zn Mineralization in the Northern Margin of North China Platform*; Geological Publishing House: Beijing, China, 1993; pp. 47–89, (In Chinese with English Abstract).
34. Faure, M.; Lin, W.; Monie, P.; Bruguier, O. Palaeoproterozoic arc magmatism and collision in Liaodong Peninsula (north-east China). *Terra Nova* **2004**, *16*, 75–80. [CrossRef]
35. Lu, X.P.; Wu, F.Y.; Guo, J.H.; Wilde, S.A.; Yang, J.H.; Liu, X.M.; Zhang, X.O. Zircon U–Pb geochronological constraints on the Palaeoproterozoic crustal evolution of the Eastern block in the North China Craton. *Precambrian Res.* **2006**, *146*, 138–164. [CrossRef]

36. Li, Z.; Chen, B. Geochronology and geochemistry of the Paleoproterozoic metabasalts from the Jiao-Liao-Ji Belt, North China Craton: Implications for petrogenesis and tectonic setting. *Precambrian Res.* **2014**, *255*, 653–667. [CrossRef]
37. Yuan, L.L.; Zhang, X.H.; Xue, F.H.; Han, C.M.; Chen, H.H.; Zhai, M.G. Two episodes of Paleoproterozoic mafic intrusions from Liaoning province, North China Craton: Petrogenesis and tectonic implications. *Precambrian Res.* **2015**, *264*, 119–139. [CrossRef]
38. Li, C.; Li, Z.; Yang, C. Palaeoproterozoic granitic magmatism in the northern segment of the Jiao-Liao-Ji Belt: Implications for orogenesis along the Eastern Block of the North China Craton. *Int. Geol. Rev.* **2017**, *60*, 217–241. [CrossRef]
39. Li, C.; Chen, B.; Li, Z.; Yang, C. Petrologic and geochemical characteristics of Paleoproterozoic monzogranitic gneisses from Xiuyan-Kuandian area in Liaodong Peninsula and their tectonic implications. *Acta Petrol. Sin.* **2017**, *33*, 963–977, (In Chinese with English Abstract).
40. Zhang, W.; Liu, F.L.; Cai, J.; Liu, C.H.; Liu, J.H.; Liu, P.H.; Liu, L.S.; Wang, F.; Yang, H. Geo-chemistry, zircon U-Pb dating and tectonic implications of the Palaeoproterozoic Ji'an and Laoling groups, northeastern Jiao-Liao-Ji Belt, North China Craton. *Precambrian Res.* **2018**, *314*, 264–287. [CrossRef]
41. Wan, Y.S.; Zhang, Q.D.; Song, T.R. SHRIMP ages of detrital zircons from the Changcheng System in the Ming Tombe area, Beijing: Constraints on the protolith nature and maximum depositional age of the Mesoproterozoic cover of the North China Craton. *Chin. Sci. Bull.* **2003**, *48*, 2500–2506.
42. Sircombe, K.N.; Freeman, M.J. Provenance of detrital zircons on the Western Australia coastline: Implications for the geologic history of the Perth Basin and denudation of the Yilgam Craton. *Geology* **1999**, *27*, 879–882. [CrossRef]
43. Wilde, S.A.; Valley, J.W.; Peck, W.H.; Graham, C.M. Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. *Nature* **2001**, *409*, 175–178. [CrossRef]
44. Luo, Y.; Sun, M.; Zhao, G.C.; Li, S.Z.; Ayers, J.C.; Xia, X.P.; Zhang, J.H. A comparison of U-Pb and Hf isotopic compositions of detrital zircons from the North and South Liaohe Groups: Constraints on the evolution of the Jiao-Liao-Ji Belt, North China Craton. *Precambrian Res.* **2008**, *163*, 279–306. [CrossRef]
45. Li, Z.; Chen, B.; Wei, C.J.; Wang, C.X.; Han, W. Provenance and tectonic setting of the Paleoproterozoic metasedimentary rocks from the Liaohe Group, Jiao-Liao-Ji Belt, North China Craton: Insights from detrital zircon U-Pb geochronology, whole-rock Sm-Nd isotopes, and geochemistry. *J. Asian Earth Sci.* **2015**, *111*, 711–732. [CrossRef]
46. Wang, X.J.; Liu, J.H.; Ji, L. Zircon U-Pb chronology, geochemistry and their petrogenesis of Paleoproterozoic monzogranitic gneisses in Kuandian area, eastern Liaoning Province, Jiao-Liao-Ji Belt, North China Craton. *Acta Petrol. Sin.* **2017**, *33*, 2689–2707.
47. Li, Z.; Chen, B.; Liu, J.W.; Zhang, L.; Yang, C. Zircon U-Pb ages and their implications for the South Liaohe Group inthe Liaodong Peninsula, Northeast China. *Acta Petrol. Sin.* **2015**, *31*, 1589–1605, (In Chinese with English Abstract).
48. Liu, F.L.; Liu, P.H.; Wang, F.; Liu, C.H.; Cai, J. Progresses and overviews of voluminous meta-sedimentary series within the Paleoproterozoic Jiao-Liao-Ji orogenic/mobile belt, North China Craton. *Acta Petrol. Sin.* **2015**, *31*, 2816–2846, (In Chinese with English Abstract).
49. Lu, X.P.; Wu, F.Y.; Lin, J.Q.; Sun, D.Y.; Zhang, Y.B.; Guo, C.L. Geochronological successions of the early Precambrian granitic magmatism in southern Liaoning Peninsula and its constraints on tectonic evolution of the North China Craton. *Chin. J. Geol.* **2004**, *39*, 123–139, (In Chinese with English Abstract).
50. Li, S.Z.; Yang, Z.S.; Liu, Y.J. Paleoproterozoic tectonic framework of the eastern North China Craton. *J. Changchun Univ. Sci. Tech.* **1995**, *25*, 14–21, (In Chinese with English Abstract).
51. Yang, Z.J.; Wang, W.; Zhao, Y.; Zhou, Y.H.; Zhang, J.; Sun, S.L.; Liu, C.C. Geochemistry and zircon U- Pb- Hf isotopes of Paleoproterozoic granitic rocks in Wangjiapuzi area, eastern Liaoning Province, and their geological significance. *Geol. Bull. Chin.* **2019**, *38*, 603–618, (In Chinese with English Abstract).
52. Dong, Y.; Bi, J.H.; Xing, D.H.; Ge, W.C.; Yang, H.; Hao, Y.J.; Ji, Z.; Jing, Y. Geochronology and geochemistry of Liaohe Group and Liaoji granitoid in the Jiao-Liao-Ji Belt, North China Craton: Implications for petrogenesis and tectonic evolution. *Precambrian Res.* **2019**, *332*, 105399. [CrossRef]
53. Li, S.Z.; Liu, Y.J.; Yang, Z.S.; Ma, R. Continental Dynamics and Regional Metamorphism of the Liaohe Group. *Geol. Rev.* **2001**, *47*, 9–18, (In Chinese with English Abstract).
54. Yang, M.C.; Chen, B.; Yan, C. Petrogenesis of Paleoproterozoic gneissic granites from Jiao-Liao-Ji Belt of North China Craton and their tectonic implications. *J. Earth Sci. Environ.* **2015**, *37*, 31–51, (In Chinese with English Abstract).
55. Chen, B.; Li, Z.; Wang, J.L.; Zhang, L.; Yan, X.L. Liaodong Peninsula ~2.2 Ga magmatic event and its geological significance. *J. Jilin Univ. (Earth Sci. Ed.)* **2016**, *46*, 303–320, (In Chinese with English Abstract).
56. Li, Z.; Chen, B.; Wei, C.J. Is the Paleoproterozoic Jiao-Liao-Ji Belt (North China Craton) a rift ntemational. *J. Earth Sci.* **2017**, *106*, 355–375.
57. Lan, T.G.; Fan, H.R.; Yang, K.F.; Cai, Y.C.; Wen, B.J.; Zhang, W. Geochronology, mineralogy and geochemistry of alkali-feldspar granite and albite granite association from the Changyi area of Jiao-Liao-Ji belt: Implications for Paleoproterozoic rifting of eastern north china craton. *Precambrian Res.* **2015**, *266*, 86–107. [CrossRef]
58. Teng, D.W.; Wang, Y.K.; Hao, X.J.; Liu, Z.H.; Zhu, K. Petrogenesis of Liao-ji Granites in Yongdian area of Liaoning and their constraints on tectonic evolution of Liao-Ji Mobile Belt. *Glob. Geol.* **2017**, *36*, 1105–1115, (In Chinese with English Abstract).
59. Liu, Y.; Li, S.; Bai, L. Structural evolution of ductile decollement zone occurred between Archaean gneiss complexes and Proterozoic Liaohe group in Haicheng area, Eastern Liaoning. *J. Changchun Univ. Earth Sci.* **1996**, *2*, 166–171.

60. Qu, H.; Zhang, Y.; Lei, G.; Wang, Z.; Cheng, P.; Zhang, F. On the Paleoproterozoic crust-mantle mixed complex in East Liaoning. *Land Resour.* **2000**, *3*, 199–205.
61. Chen, S.; Huan, Y.; Bing, Z. Characteristics of Paleo-Proterozoic intrusive rocks and continental dynamic evolution pattern of tectonomagma in east Liaoning. *Liaoning Geol.* **2001**, *1*, 43–51, (In Chinese with English Abstract).
62. Hao, D. *The Origin of Paleoproterozoic Granites in the Eastern Liaoning and Southern Jilin Provinces and the Crustal Evolution*; Ocean University of China: Qingdao, China, 2004.
63. Wu, F.Y.; Zhang, Y.B. Genesis of zircon and its constraints on interpretation of U-Pb age. *Chin. Sci. Bull.* **2004**, *49*, 1554–1569. [CrossRef]
64. Wan, Y.S.; Ma, M.Z.; Dong, C.Y.; Xie, H.Q.; Xie, S.W.; Ren, P.; Liu, D.Y. Widespread late Neoarchean reworking of Meso- to Paleoarchean continental crust in the Anshan-Benxi area, North China Craton, as documented by U–Pb–Nd–Hf–O isotopes. *Am. J. Sci.* **2015**, *315*, 620–670. [CrossRef]
65. Wan, Y.S.; Dong, C.Y.; Peng, R.; Bai, W.Q.; Xie, H.Q.; Liu, S.J. Spatial and temporal distribution, compositional characteristics and formation and evolution of Archean TTG rocks in the North China Craton: A synthesis. *Acta Petrol. Sin.* **2017**, *33*, 1405–1419.
66. Wan, Y.S.; Dong, C.Y.; Xie, H.Q.; Xie, S.W.; Liu, S.J.; Bai, W.Q.; Ma, M.Z.; Liu, D.Y. Formation Age of BIF-Bearing Anshan Group Supracrustal Rocks in Anshan-Benxi Area: New Evidence from SHRIMP U-Pb Zircon Dating. *Earth Sci.* **2017**, *43*, 57–81, (In Chinese with English Abstract).
67. Wen, F.; Tian, Z.H.; Liu, P.H.; Xu, W.; Liu, F.L.; Mitchell, N.R. Sedimentary evidence for the early Paleoproterozoic tectono-magmatic lull: Detrital zircon provenance of the 2.47-2.17 Ga Langzishan Formation, Liaohe Group, Eastern Block of the North China Craton. *J. Asian Earth Sci.* **2021**, *221*, 104939. [CrossRef]
68. Wu, D.; Liu, Y.J.; Li, W.M.; Chang, R.H. Ductile shear zone and uranium mineralization in the Lianshanguan area of eastern Liaoning uranium metallogenic belt. *Acta Petrol. Sin.* **2020**, *36*, 2571–2588, (In Chinese with English Abstract).
69. Wang, H.C.; Lu, S.N.; Chu, H.; Xiang, Z.Q.; Zhang, C.J.; Liu, H. Zircon U-Pb age and tectonic setting of meta-basalts of Liaohe Group in Helan area, Liaoyang, Liaoning Province. *J. Jilin Univ. (Earth Sci. Ed.)* **2010**, *41*, 1322–1334, (In Chinese with English Abstract).
70. Wu, D. *Early Precambrian Tectonic Evolution and Uranium Mineralizationin Lianshanguan Area, Eastern Liaoning Province*; Jilin University: Changchun, China, 2021; (In Chinese with English Abstract).
71. Yang, C.W.; Zhang, J.; Zhao, L.F.; Zhang, C.; Yang, H.X.; Lu, T.J. Detrital zircon constraints on tectonic evolution of the liaodong paleoproterozoic orogenic belt, north china craton. *Precambrian Res.* **2021**, *362*, 106152. [CrossRef]
72. Zhao, L.; Zou, H.; Qu, H.; Lv, X.; Hou, J. Preliminary study on the regional correlation of Liaohe group in eastern Liaoning. China. *Geol. Resour.* **2011**, *20*, 265–267, (In Chinese with English Abstract).
73. Zhai, F.; Liang, S.; Guo, H. The original formation-based discussion on Liaohe Group's environment. *Contrib. Geol. Miner. Resour. Res.* **2016**, *31*, 550–554, (In Chinese with English Abstract).
74. Andersen, T. Correction of common lead in u_pb analyses that do not report 204Pb. *Chem. Geol.* **2002**, *192*, 59–79. [CrossRef]
75. Blank, L.P.; Kamo, S.L.; Williams, I.S.; Mundil, R.; Davis, D.W.; Korsch, R.J.; Foudoulis, C. The application of SHEIMP to Phanerozoic geochronology: A critical appraisal of four zircon standards. *Chem. Geol.* **2003**, *200*, 171–188.
76. Ludwig, K.R. *ISOPLOT 3.00, A Geochronology Toolkit for Microsoft Excel*; Berkeley Geochronological Center Special Publication: Berkeley, CA, USA, 2003.
77. Diwu, C.R.; Sun, Y.; Guo, A.L.; Wang, H.L.; Liu, X.M. Crustal growth in the North China Craton at ~2.5 Ga: Evidence from in situ zircon U-Pb ages, Hf isotopes and whole-rock geochemistry of the Dengfeng Complex. *Gondwana Res.* **2011**, *20*, 149–170. [CrossRef]
78. Geng, Y.S.; Shen, Q.H.; Ren, L.D. Late Neoarchean to Early Paleoproterozoic magmatic events and tectono-thermal systems in the North China Craton. *Acta Petrol. Sin.* **2010**, *26*, 1945–1966.
79. Geng, Y.S.; Du, L.L.; Ren, L.D. Growth and reworking of the early Precambrian continental crust in the North China Craton: Constraints from zircon Hf isotopes. *Gondwana Res.* **2012**, *21*, 517–529. [CrossRef]
80. Guan, H.; Sun, M.; Wilde, S.A.; Zhou, X.H.; Zhai, M.G. SHRIMP U-Pb zircon geochronology of the Fuping complex: Implications for formation and assembly of the North China Craton. *Precambrian Res.* **2002**, *113*, 1–18. [CrossRef]
81. Liu, F.; Guo, J.H.; Lu, X.P.; Diwu, C.R. Crustal growth at ~2. 5Ga in the North China Craton: Evidence from whole-rock Nd and zircon Hf isotopes in the Huai'an gneiss terrane. *Chin. Sci. Bull.* **2009**, *24*, 4704–4713.
82. Liu, J.H.; Liu, F.L.; Ding, Z.J.; Liu, P.H.; Wang, F. The zircon Hf isotope characteristics of ~2.5Ga magmatic event, and implication for the crustal evolution in the Jiaobei terrane, China. *Acta Petrol. Sin.* **2012**, *28*, 2697–2704.
83. Luo, Y.; Sun, M.; Zhao, G.C.; Li, S.Z.; Xu, P.; Ye, K.; Xia, X.P. LA–ICP–MS U–Pb zircon ages of the Liaohe Group in the Eastern Block of the North China Craton: Constraints on the evolution of the Jiao-Liao-Ji Belt. *Precambrian Res.* **2004**, *134*, 349–371. [CrossRef]
84. Jahn, B.M.; Liu, D.Y.; Wan, Y.S.; Song, B.; Wu, J.S. Archean crustal evolution of the Jiaodong Peninsula, China, as revealed by zircon SHRIMP geochronology, elemental and Nd-isotope geochemistry. *Am. J. Sci.* **2008**, *308*, 232–269. [CrossRef]
85. Zhao, G.C.; Wilde, S.A.; Cawood, P.A.; Sun, M. SHRIMP U-Pb zircon ages of the Fuping complex: Implications for late archean to paleoproterozoic accretion and assembly of the North China Craton. *Am. J. Sci.* **2002**, *302*, 191–226. [CrossRef]
86. Li, S.Z.; Zhao, G.C.; Santosh, M.; Liu, X.; Dai, L.M. Paleoproterozoi Tectonothermal Evolution and Deep Crustal Processes in the JiaoLiao-Ji Belt, North China Craton: A Review. *Geol. J.* **2011**, *46*, 525–543. [CrossRef]

87. Li, S.Z.; Dai, L.; Zhang, Z.; Zhao, S.; Guo, L. Precambrian geodynamics (III): General features of Precambrian geology. *Earth Sci. Front.* **2015**, *22*, 27–45.
88. Wang, F.; Liu, F.L.; Liu, P.H.; Cai, J.; Schertl, H.P.; Ji, L.S.; Tian, Z.H. In situ zircon U-Pb dating and whole-rock geochemistry of metasedimentary rocks from South Liaohe Group, Jiao-Liao-Ji orogenic belt: Constraints on the depositional and metamorphic ages, and implications for tectonic setting. *Precambrian Res.* **2017**, *303*, 764–780. [CrossRef]
89. Wang, X.P.; Peng, P.; Wang, C.; Yang, S.Y. Petrogenesis of the 2115Ma Haicheng mafic sills from the eastern North China Craton: Implications for an intra-continental rifting. *Gondwana Res.* **2016**, *39*, 347–364. [CrossRef]
90. Liu, F.; Liu, C.; Itano, K.; Iizuka, T.; Cai, J.; Wang, F. Geochemistry, U-Pb dating, and Lu-Hf isotopes of zircon and monazite of porphyritic granites within the Jiao-Liao-Ji orogenic belt: Implications for petrogenesis and tectonic setting. *Precambrian Res.* **2017**, *300*, 78–106. [CrossRef]
91. Wan, Y.S.; Liu, D.Y.; Song, B.; Wu, J.S.; Yang, C.H.; Zhang, Z.Q.; Geng, Y.S. Geochemical and Nd isotopic compositions of 3.8 Ga meta-quartz dioritic and trondhjemitic rocks from the Anshan area and their geological significance. *J. Asian Earth Sci.* **2005**, *24*, 563–575. [CrossRef]
92. Wan, Y.S.; Liu, D.Y.; Nutman, A.; Zhou, H.Y.; Dong, C.Y.; Yin, X.Y.; Ma, M.Z. Multiple 3.8–3.1 Ga tectono-magmatic events in a newly discovered area of ancient rocks (the Shengousi Complex), Anshan, North China Craton. *J. Asian Earth Sci.* **2012**, *54–55*, 18–30. [CrossRef]
93. Wu, F.Y.; Zhang, Y.B.; Yang, J.H.; Xie, L.W.; Yang, Y.H. Zircon U–Pb and Hf isotopic onstraints on the Early Archean crustal evolution in Anshan of the North China Craton. *Precambrian Res.* **2008**, *167*, 339–362. [CrossRef]
94. Cui, P.L.; Sun, J.G.; Sha, D.M.; Wang, X.J.; Zhang, P.; Gu, A.L.; Wang, Z.Y. Oldest zircon xenocryst (4.17 Ga) from the North China Craton. *Int. Geol. Rev.* **2013**, *55*, 1902–1908. [CrossRef]
95. Liu, P.H.; Liu, F.L.; Wang, F. In-situ U-Pb dating of zircons from high-pressure granulites in Shandong Peninsula Eastern China and its geological significance. *Earth Sci. Front.* **2011**, *18*, 33–54.
96. Belousova, E.A.; Griffin, W.L.; O'Reilly, S.Y.; Fisher, N.I. Igneous zircon: Trace element composition as an indicator of source rock type. *Contrib. Mineral. Petrol.* **2002**, *143*, 602–622. [CrossRef]
97. EI-Bialy, M.Z.; Ali, K.A. Zircon trace element geochemical constraints on the evolution of the Ediacaran (600–614 Ma) post-collisional DokhanV olcanics and Y ounger Granites of SE Sinal, NE Arabian-Nubian Shield. *Chem. Geol.* **2013**, *360*, 54–73. [CrossRef]
98. Grimes, C.B.; John, B.E.; Kelemen, P.B.; Mazdab, F.K.; Wooden, J.L.; Cheadle, M.J.; HanghØj, K.; Schwartz, J.J. Trace element chemistry of zircons from oceanic crust: A method for distinguishing detrital zircon provenance. *Geology* **2007**, *35*, 643–646. [CrossRef]
99. Yang, J.H.; Gawood, P.A.; Du, Y.S.; Huang, H.; Huang, H.W.; Tao, P. Large Igneous Province and magmatic arc sourced Permian-Triassic volicanogenic sediments in China. *Sediment. Geol.* **2012**, *261*, 120–131. [CrossRef]
100. Chen, J.S.; Xing, D.H.; Liu, M.; Li, B.; Yang, H.; Tian, D.X.; Yang, F.; Wang, Y. Zircon U-Pb chronology and geological significance of felsic volcanic rocks in the Liaohe Group from the Liaoyang area, Liaoning Province. *Acta Petrol. Sin.* **2017**, *33*, 2792–2810.
101. Ludwig, K.R. User's Manual for Isoplot 3.70. In *A Geochronological Toolkit for Microsoft Excel*; Berkley Geochronology Centre Special Publication: Berkeley, CA, USA, 2008.
102. Tucker, R.T.; Roberts, E.M.; Hu, Y.; Kemp, A.I.S.; Salisbury, S.W. Detrital zircon age constraints for the Winton Formation, Queensland: Contextualizing Australia's Late Cretaceous dinosaur faunas. *Gondwana Res.* **2013**, *24*, 767–779. [CrossRef]
103. Song, Y.; Zhang, D.X.; Andrei, S.; Yuan, M.M.; Cong, X.R. Decomposition the detrital grain ages by Kernel Density Estimation and its applications: Determining the major tectonic events in the Songliao Basin, NE China. *Earth Sci. Front.* **2016**, *23*, 265–276, (In Chinese with English Abstract).
104. Wang, F.; Liu, F.; Schertl, H.P.; Xu, W.; Tian, Z. Detrital zircon U-Pb geochronology and hf isotopes of the Liaohe group, Jiao-Liao-ji belt: Implications for the Paleoproterozoic tectonic evolution. *Precambrian Res.* **2020**, *340*, 105633. [CrossRef]
105. Liu, J.; Zhang, J.; Liu, Z.; Yin, C.; Zhao, C.; Li, Z. Geochemical and geochronological study on the Paleoproterozoic rock assemblage of the Xiuyan region: New constraints on an integrated rift-and-collision tectonic process involving the evolution of the Jiao-Liao-Ji belt, North China Craton. *Precambrian Res.* **2018**, *310*, 179–197. [CrossRef]
106. Meng, E.; Liu, F.; Liu, P.; Liu, C.; Shi, J.; Kong, Q. Depositional ages and tectonic implications for South Liaohe group from Kuandian area in northeastern Liaodong Peninsula, northeast China. *Acta Petrol. Sin.* **2013**, *29*, 2465–2480.
107. Meng, E.; Wang, C.; Li, Y.; Li, Z.; Yang, H.; Cai, J.; Ji, L.; Jin, M. Zircon U–Pb–Hf 1278 isotopic and whole-rock geochemical studies of Paleoproterozoic metasedimentary rocks in 1279 the northern segment of the Jiao–Liao–Ji Belt, China: Implications for provenance and 1280 regional tectonic evolution. *Precambrian Res.* **2017**, *298*, 472–489. [CrossRef]
108. Qin, Y. *Geochronological Constraints on the Tectonic Evolution of the Liao-Ji 1297 Paleoproterozoic Rift Zone*; Jilin University: Changchun, China, 2013; (In Chinese with English Abstract).
109. Wang, F.; Liu, J.; Liu, C. Detrital zircon U-Pb geochronology of metasedimentary rocks from the Lieryu Formation of the South Liaohe Group in Sanjiazi area, the South Liaoning Province. *Acta Petrol. Sin.* **2017**, *33*, 2785–2791.
110. Wang, F.; Liu, F.L.; Liu, P.H.; Cai, J.; Ji, L.; Liu, L.S.; Tian, Z.H. Redefinition of the Gaixian formation of the South Liaohe group: Evidence from the detrital zircon U-Pb geochronology of metamorphosed sandstone in Huanghuadian-Suzigou area, the southern Liaoning Province. *Acta Petrol. Sin.* **2018**, *34*, 1219–1228.

111. Wang, H.C.; Ren, Y.W.; Lu, S.N. Stratigraphic Units and Tectonic Setting of the Paleoproterozoic Liao–Ji Orogen. *Acta Geosci. Sin.* **2015**, *36*, 583–598, (In Chinese with English Abstract).
112. Xu, W.; Liu, F.L.; Liu, P.H.; Tian, Z.H.; Cai, J.; Wang, W.; Ji, L. Paleoproterozoic transition in tectonic regime recorded by the Eastern Block of the North China Craton: Evidence from detrital zircons of the Langzishan Formation, Jiao-Liao-Ji Belt. *Int. Geol. Rev.* **2020**, *62*, 168–185. [CrossRef]
113. Xu, W.; Liu, F.L.; Wang, F.; Santosh, M.; Dong, Y.S.; Li, S. Palaeoproterozoic tectonic evolution of the Jiao-Liao-Ji Belt, North China Craton: Geochemical and isotopic evidence from ca. 2.17 Ga felsic tuff. *Geol. J.* **2020**, *55*, 409–424. [CrossRef]
114. Liu, P.H.; Liu, F.L.; Tian, Z.H.; Cai, J.; Ji, L.; Wang, F. Petrological and geochronological evidence for Paleoproterozoic granulite-facies metamorphism of the South Liaohe Group in the Jiao-Liao-Ji Belt, North China Craton. *Precambrian Res.* **2019**, *327*, 121–143. [CrossRef]
115. Wen, F.; Tian, Z.H. A metamorphic and deformational study of meta-pelites in the Liaohe Group located at Liaodong Peninsula: Significance to process of Paleoproterozoic orogenesis and exhumation. *Acta Petrol. Sinica* **2021**, *37*, 619–635.
116. Tian, Z.H.; Liu, F.L.; Windley, B.F.; Liu, P.H.; Wang, F.; Liu, C.H.; Wang, W.; Cai, J.; Xiao, W.J. Polyphase structural deformation of low-to medium-grade metamorphic rocks of the Liaohe Group in the Jiao-Liao-Ji Orogenic Belt, North China Craton: Correlations with tectonic evolution. *Precambrian Res.* **2017**, *303*, 641–659. [CrossRef]
117. Bi, J.H.; Ge, W.C.; Xing, D.H.; Yang, H.; Dong, Y.; Tian, D.X.; Chen, H.J. Paleoproterozoic meta-rhyolite and meta-dacite of the Liaohe Group, Jiao-Liao-Ji Belt, North China Craton: Petrogenesis and implications for tectonic setting. *Precambrian Res.* **2018**, *314*, 306–324. [CrossRef]
118. Lu, X.P.; Wu, F.Y.; Guo, J.H.; Yin, C.J. Late Paleoproterozoic granitic magmatism and crustal evolution in the Tonghua region, northeast China. *Acta Petrol. Sin.* **2005**, *21*, 721–736, (In Chinese with English Abstract).
119. Cawood, P.; Hawkesworth, C.J.; Dhuime, B.; Prave, T. Detrital zircon record and tectonic setting. *Geology* **2012**, *40*, 875–878. [CrossRef]
120. Li, Z.; Chen, B.; Wei, C. Hadean detrital zircon in the North China Craton. *J. Mineral. Petrol. Sci.* **2016**, *111*, 283–291. [CrossRef]
121. Zhu, K.; Liu, Z.; Xu, Z.; Wang, X.A.; Cui, W.; Hao, Y. Petrogenesis and tectonic implications of two types of Liaoji granitoid in the Jiao-Liao-Ji Belt, North China Craton. *Precambrian Res.* **2019**, *331*, 105369. [CrossRef]
122. Liu, P.H.; Cai, J.; Zou, L. Metamorphic P-T-t path and its geological implication of the Sanjiazi garnet amphibolites from the northern Liaodong Penisula, Jiao-Liao-Ji belt: Constraints on phase equilibria and Zircon U-Pb dating. *Acta Petrol. Sin.* **2017**, *33*, 2649–2674, (In Chinese with English Abstract).
123. Yang, C.; Liu, J.; Yang, H.; Zhang, C.; Feng, J.; Lu, T.; Sun, Y.; Zhang, J. Tectonics of the Paleoproterozoic Jiao-Liao-Ji orogenic belt in the Liaodong peninsula, North China Craton: A review. *J. Asian Earth Sci.* **2019**, *176*, 141–156. [CrossRef]
124. Xu, W.; Liu, F.; Tian, Z.; Liu, L.; Ji, L.; Dong, Y. Source and petrogenesis of Paleoproterozoic meta-mafic rocks intruding into the north Liaohe Group: Implications for back-arc extension prior to the formation of the Jiao-Liao-Ji belt, north china craton. *Precambrian Res.* **2018**, *307*, 66–81. [CrossRef]
125. Gerya, T. Future directions in subduction modeling. *J. Geodyn.* **2011**, *52*, 344–378. [CrossRef]

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