1. Petrographic description for other samples

1.1. Samples from the Langzishan Fm.

Sample15LSG49-1 is a quartz sandstone, with the clastic particles mainly consisting of quartz (~90%), alkali feldspar (7%), and a small amount of dark minerals (3%). Alkali feldspar is mostly microcline with gridiron twining (Fig. 14a).

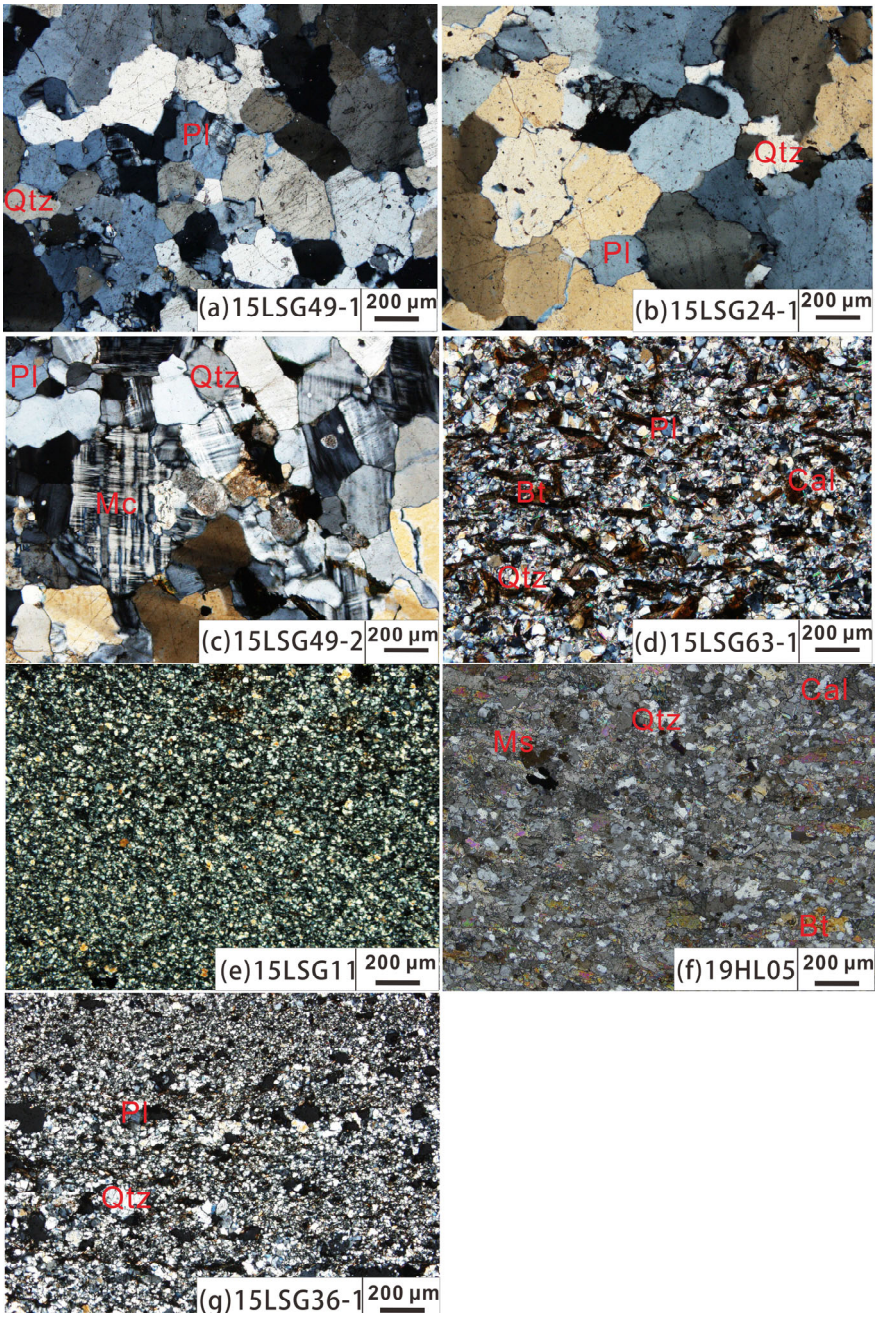

Figure S1. Supplementary thin-section micrographs of the Langzishan Fm. and the Li'eryu Fm. in the North Liaohe Group. (**a**) the sample 15LSG49-1 (quartz sandstone), (**b**) the sample 15LSG24-1 (quartz sandstone), (**c**) the sample 15LSG49-2 (quartz sandstone), (**d**) the sample 15LSG63-1 (meta-sandstone), (**e**) the sample 15LSG11 (siltstone), (**f**) the sample 19HL05 (meta-sandstone), (**g**) the sample 15LSG36-1 (meta-quartz sandstone). The abbreviations for the minerals are, Qtz-quartz, Mc-microcline, Pl-plagioclase, Ms-muscovite, Cal-calcite, Bt-biotite.

Sample 15LSG24-1 and 15LSG49-2 are feldspathic quartz sadstones, and the minerals mainly consist of quartz (85%), alkali feldspar (12%), and a small proportion of dark minerals (3%). The rocks are well-sorted, with contact cementation and particle support observed (Fig. 14b and c).

Sample 15LSG63-1 is a meta-sandstone, characterized by a mineral assemblage of quartz (45%), alkaline feldspar (25%), biotite (15%), calcite (8%), muscovite (5%), and a small proportion of dark minerals (2%). The rock's cement is calcareous, with contact cementation and particle support observed (Fig. 14d).

Sample 19LSG11 is a siltstone, exhibiting a silty structure. The clastic particles are mainly composed of quartz (70%), feldspar (20%), and muscovite (8%), with a small proportion of dark minerals (2%). The rock is well-sorted, with contact cementation and particle support evident (Fig. 14e).

1.2. Samples from the Li'eryu Fm.

Sample 19HL05 is meta-sandstones, characterized by a mineral assemblage of quartz (45%), alkaline feldspar (25%), calcite (10%), biotite (13%), muscovite (5%), and a small proportion of dark minerals (2%). The rock's cement is calcareous, with contact cementation and particle support observed (Fig. 14f).

Sample 15LSG36-1 is meta-quartz sandstone, characterized by a mineral assemblage of quartz (~85%), alkaline feldspar (8%), biotite (~5%), and a small proportion of dark minerals (2%). The rock's cement is calcareous, with contact cementation and particle support observed (Fig. 14g).

2. Supplementary results of the detrital zircon U-Pb LA-ICP-MS ages

2.1. The Langzishan Fm.

Zircon grains selected from the quartz sandstone (15LSG49-1) in the bottom layer of the Langzishan Fm., are light brown and subhedral with a short columnar shape and aspect ratios of less than 2.5:1 (Fig. 6a). A total of 60 zircons were analyzed, which showed oscillatory zonings with Th/U ratios ranging from 0.17 to 1.72, indicating that they are typical magmatic zircons. Out of the 60 zircons, 50 were concordant, most yielding $^{207}Pb/^{206}Pb$ ages in the range 2433-2736 Ma, with an age peak at 2538 ± 13 Ma. A small number of grains gave a young age of 2239 ± 14 Ma and some gave an older age of 2876 ± 10 Ma (Fig. 7a).

Two zircons extracted from the pebbly quartz sandstones (15LSG37-1 and 19LSG07) are subhedral, prismatic, or rounded in shape with a length of approximately 60-100 μm and a width of 40-70 μm (Fig. 6b and c). Out of the 60 zircons analyzed from 15LSG37-1, 48 yielded concordant data showing $^{206}Pb/^{207}Pb$ ages of 2190-3031 Ma, with an age peak at 2508 ± 17 Ma (Fig.7b). The analyzed zircons in 19LSG07 showed oscillatory zonings with Th/U ratios ranging from 0.51-1.54, indicating that they are typical magmatic zircons. 17 concordant data yielded $^{206}Pb/^{207}Pb$ ages of 2437-2547 Ma with an age peak at 2491 ± 14 Ma (Fig. 7c).

The zircon grains from feldspathic quartz sandstones (15LSG24-1 and 15LSG49-2) are subhedral, prismatic, or oval in shape with aspect ratios of less than 3:1 (Fig. 6d and e). The analyzed zircons from 15LSG24-1 showed oscillatory zonings with Th/U ratios of 0.19-1.20, indicating that they are typical magmatic zircons. Out of the 56 effective data points, $^{206}Pb/^{207}Pb$ ages of 2105-2564 Ma were obtained, with an age peak at 2465 ±16 Ma (refer to Fig. 7d). The analyzed zircons from 15LSG49-2 showed obvious oscillatory zonings with Th/U ratios of 0.19-1.28, indicating that they are typical magmatic zircons. 54 effective data points yielded $^{206}Pb/^{207}Pb$ ages of 2368-2678 Ma, with an age peak at 2525 ± 14 Ma. The other two analyzed points yielded two older ages of 3187 ± 20 Ma and 4226 ± 18 Ma (Fig. 7e).

The metamorphic sandstone sample (15LSG63-1) contains light brown zircons that are short columnar with aspect ratios up to 2:1 and subhedral shapes. The majority of zircons are magmatic zircons, as indicated by CL image results (Fig. 6f), except for one zircon (2160 ± 43 Ma) that is identified as a metamorphic zircon by the zircon CL image.

Of the 60 zircons analyzed, 46 yielded effective data with $^{206}Pb/^{207}Pb$ ages ranging from 2457-2713 Ma, and the weighted average age was 2488 ± 13 Ma (Fig. 7f). The zircons display oscillatory zonings with Th/U ratios ranging from 0.37 to 4.17.

The siltstone sample (19LSG06) contains small, subhedral, short prismatic or oval zircon grains with subhedral shapes and aspect ratios less than 2:1, as shown by CL images (Fig. 6g). The 80 zircons analyzed showed dense oscillatory or patched zonings with Th/U ratios ranging from 0.31-1.19. Of the 49 effective data, $^{206}Pb/^{207}Pb$ ages ranged from 2378-2622 Ma, with the age peak at 2516 ± 8.2 Ma (Fig. 7g). Five analytical points gave younger age range of 2113-2210 Ma, and the peak was at 2173 ± 31 Ma.

Zircons from the quartz sandstone samples (19LSG02-2 and 19LSG04) are light brown, short columnar, and have aspect ratios less than 3:1 (Fig. 6h and i). Of the 54 effective analytical zircons from 19LSG02-2, Th/U ratios ranged from 0.29-1.47, with $^{206}Pb/^{207}Pb$ ages ranging from 2446-2747 Ma (Fig. 7h). The age peak was at 2563 ± 14 Ma, and there were two older ages of 3113 ± 16 Ma and 3309 ± 18 Ma and a younger age of 2226 ± 38 Ma. Of the 70 zircons analyzed from 19LSG04, 46 effective data yielded $^{206}Pb/^{207}Pb$ ages ranging from 2456-2678 Ma, and the age peak was at 2532 ± 13 Ma (Fig. 7i). The zircons showed oscillatory zonings with Th/U ratios ranging from 0.31 to 1.33 and are typical magmatic zircons. Another younger age of 2214 ± 30 Ma and an older age of 2959 ± 18 Ma were also present.

The zircon grains extracted from sample 19LSG14, which is a garnet mica schist, exhibit short columnar and euhedral morphology with aspect ratios less than 2.5:1 (Fig. 6j). Among the analyzed 84 zircons, only one grain has a Th/U ratio of 0.08 while the rest show oscillatory zonings and Th/U ratios ranging from 0.32 to 1.85, indicating they are typical magmatic zircons. Out of 54 effective data, the $^{206}Pb/^{207}Pb$ age ranges from 1945 to 2671 Ma, with the main age peak at 2505 ± 19 Ma and a secondary peak at 2185 ± 36 Ma (Fig. 7j).

The zircon grains from the siltstone sample (19LSG11) have a short columnar, semi-idiomorphic shape with aspect ratios less than 2.5:1 (Fig. 6k). The analyzed 40 zircons exhibit oscillatory zonings and Th/U ratios ranging from 0.30 to 1.15, indicating that they are also typical magmatic zircons. Among the 22 effective data, the $^{206}Pb/^{207}Pb$ age were 2117-2581Ma with an age peak at 2341 ± 53 Ma (Fig. 7k).

2.2. The Li'eryu Fm.

Zircon grains extracted from metamorphic sandstones (19HL05-2 and 19LSG15) are short columnar or rounded with aspect ratios less than 2:1 (Fig. 6l and m). Of the 80 zircons analyzed from sample 19HL05, 74 effective data points yielded an $^{206}Pb/^{207}Pb$ age of 2125 ± 15 Ma with an age peak at 2125 ± 15 Ma. These zircons show oscillatory zoning with Th/U ratios ranging from 0.08 to 0.88. For sample 19LSG15, the 70 zircons analyzed also show oscillatory zoning with Th/U ratios ranging from 0.33 to 1.20, and 55 effective data points yielded an $^{206}Pb/^{207}Pb$ age range of 2056-2270 Ma with an age peak at 2171 ± 10 Ma. Two older ages of 2513 ± 20 Ma and 2514 ± 19 Ma are also presented (Fig. 7m).

In sample 19LSG13, zircon grains extracted from the siltstone are small and short columnar, with aspect ratios less than 2:1 (Fig. 6n). The 80 zircons analyzed show oscillatory zoning and are typical magmatic zircons. Of the 53 effective data points, the $^{206}Pb/^{207}Pb$ age range was 2077-2295 Ma with an age peak at 2206 ± 25 Ma (Fig. 7n). Three other analysis points yielded older ages of 2479 ± 18 Ma, 2506 ± 17 Ma, and 2605 ± 17 Ma.

Zircon grains picked out from metamorphic sandstone (sample 15LSG36-1) are light brown, short columnar, and have aspect ratios less than 2.5:1 (Fig. 6o). Of the 60 zircons analyzed, some zircons have varying degrees of lead loss, but all show typical magmatic zircon oscillatory zoning. Of the 14 effective data points, the $^{206}Pb/^{207}Pb$ age range was 2042-2220 Ma, with an age peak at 2221 ± 43 Ma. Another young age of 1846 ± 18 Ma and an older age of 2483 ± 15 Ma were also obtained (Fig. 7o).