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Activation of northern margin of the North China Craton in Late Paleozoic: Evidence from U-Pb dating and Hf isotopes of detrital zircons from the Upper Carboniferous Taiyuan Formation in the Ningwu-Jingle basin

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LA-MC-ICPMS U-Pb dating has been performed on detrital zircons from the Upper Carboniferous Taiyuan Formation (N-8) in the Ningwu-Jingle Basin, west of the North China Craton (NCC). The ages of 72 detrital zircon grains are divided into three groups: 303—320 Ma (6 grains), 1631—2194 Ma (37 grains, peaked at 1850 Ma), 2318—2646 Ma (29 grains, peaked at 2500 Ma). Detrital zircons of Group 2 and Group 3 were likely derived from the basement of the NCC. Group 1 zircons exhibit $^{176}Hf/^{177}Hf$ ratios ranging from 0.281725 to 0.282239, with corresponding negative $\varepsilon_{Hf}(t)$ values of –12.4—–30.3 and old Hf model ages of 1.4—2.2 Ga. These characteristics show a strong resemblance to those of Carboniferous igneous zircons from the Inner Mongolia Paleo-uplift (IMPU) on the northern margin of the NCC, but differ significantly from those of the Xing-Meng Orogenic Belt, suggesting that the source of the Taiyuan Formation partly came from the IMPU. All detrital zircons of Group 1 have relatively high Th/U ratios (> 0.67), indicating a magmatic origin. The mean age (304 ± 6 Ma) of the two youngest grains is close to the depositional age of the Taiyuan Formation, suggesting a strong tectonic uplift and magmatism in the IMPU during the Late Carboniferous. This paper provides important geological evidence for the activation of the northern margin of the NCC in the Late Paleozoic.

North China Craton, Taiyuan Formation, Ningwu-Jingle basin, detrital zircon, LA-MC-ICPMS U-Pb dating, provenance analysis

The evolution[1,2] of the North China Craton (NCC) has been a hot topic in recent geological research. The model of "lithosphere thinning" was proposed by domestic and overseas scientists in the 1990s[3−6]. Recently, this concept has evolved into "cratonic destruction"[7]. Although the duration of lithosphere thinning and destruction of the NCC is a key issue, the onset of the activation of the NCC remains largely controversial. It is generally thought that the NCC remained stable from the Neoproterozoic to the Early Triassic[8−10]. Recently, Carboniferous calc-alkaline, I-type magmatic arc plutonism has been identified in the Inner Mongolia Paleo-uplift (IMPU)[11−13], implying that the northern margin of the NCC might have been activated during the Late Paleozoic. However, because of the deep emplacement of these intrusions and the lack of contemporaneous volcanic rocks[14], no surface geological evidence for this activation has been discovered. Information about lithosphere evolution and magmatism is preserved in sedimentary rocks. For example, a rapid, kilometer-scale

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crustal doming took place and classic rocks developed around the doming prior to the eruption of the Emeishan flood basalts in the Late Permian[15]. The Dabie orogenic belt uplifted rapidly during the Early-Middle Jurassic and provided a sediment source for the Hefei Basin[16]. Therefore, studies of source provenance and characteristics of the Late Paleozoic classic rocks of the NCC provide insights into the cratonic evolution.

Zircon possesses the highest closure temperature of the U-Pb system among all known minerals[17], and its Lu-Hf isotopic system is relatively immune to later tectonothermal events[18]. Consequently, combined U-Pb and Hf isotopic analyses of detrital zircons have become an efficient and reliable method for provenance analyses and paleogeographic reconstruction[12,19−22]. This paper reports LA-MC-ICPMS U-Pb ages and *in situ* Hf isotope analyses of detrital zircons of Upper Carboniferous sedimentary rocks from the Ningwu-Jingle basin of Shanxi Province (hinterland of the NCC). Based on these data, we analyzed the characteristics and discussed the source provenance of the Carboniferous Formation. It is suggested that the activation of the northern margin of the NCC took place as early as in the Late Paleozoic.

1 Geological setting

During the Paleozoic, subductions of oceanic plates underneath both the southern and northern margins of the NCC created two continental magmatic arc belts, one on the southern margin[23,24] during the Early Paleozoic and the other on the northern margin[12,13] during the Late Paleozoic. This paper concerns the Xing-Meng Orogenic Belt (XMOB) and the northern margin of the NCC. The XMOB is the east part of the Central Asian Orogenic Belt. It is a typical Phanerozoic complex orogenic belt formed by the successive accretion of arc complexes, accompanied by emplacement of voluminous lavas and granitic magmas from the Paleozoic to the Mesozoic age[25−30]. The northern margin of the NCC is composed of the IMPU in the north and the Yanshan thrust-and-fold belt in the south, which are separated by the Chicheng-Shangyi fault[31−33] (Figure 1(a)). Late Carboniferous magmatism within the NCC is mainly distributed in the IMPU, with emplacement ages being predominantly between 324 and 300 Ma[11,13,34].

The Ningwu-Jingle basin, located in the upper mid-west of Shanxi Province (Figure 1(a)), is a NE-SW trending syncline between the Luya Mt and the Yunzhong Mt. The core of this syncline is made up of Jurassic strata, while the wings, which have steep strikes, are composed of Triassic, Permian, Carboniferous, Ordovician, and Cambrian strata (Figure 1(b), (c)), and locally of the Archean metamorphic rocks. Only middle-upper part of the Carboniferous formation was preserved in the basin. It lies unconformablly on the Middle Ordovician Majiagou Formation. The Carboniferous formation is about 100 m thick and is mainly composed of quartzose sandstones and shale with a coal-bearing interlayer. The Taiyuan Formation of the Upper Carboniferous is an interventing marine and terrestrial sequence with a coal-bearing deposit. Underlain by the Benxi Formation and overlain by the Shanxi Formation of the Upper Permian, it is composed mainly of gray black shale, sandy shale, carbonaceous shale, gray quartzose sandstones and a coal-bearing, limestone, marine face shale interlayer. The Taiyuan Formation, 84.4—118.9 m thick, contains standard animal fossils such as *Pseudoschwagerina, Ddictyoclostus taiyunfuensis* (*Graban*), and plant fossils such as *Neuropteris ovata* and *Lepidodendron posthumii*[35], indicative of an depositional age of about 310—300 Ma (Chinese strata standard[36]). The sample selected for this study (N-8) is quartzose sandstone, which belongs to the upper section of the Taiyuan Formation.

2 Analytical methods

The size of detrital zircons varies between 50—250 μm. Zircons range from prismatic or rounded to subhedral in shape, showing some sedimentary abrasion. The zircons were mounted in epoxy before about 1/3 of mass was polished off. To maintain randomness within detrital zircon study, no cathodoluminescence (CL) imaging was performed prior to analysis.

Zircon U-Pb dating was performed by Laser-Ablation-Inductivity Couple Plasma Mass Spectrometry (LA-ICPMS, Agilent 7500a) at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (Wuhan). The laser-ablation system is a GeoLas 2005 equipped with a 193 nm ArF-excimer laser and a homogenizing, imaging optical system. A 30 μm spot size and 80 Hz energy density were adopted. The standard 91500 zircons (age 1064 Ma) were used for calibration of interelement fractionation, and U, Th and Pb concentrations were determined based on the standard NIST610. The Glitter pro-

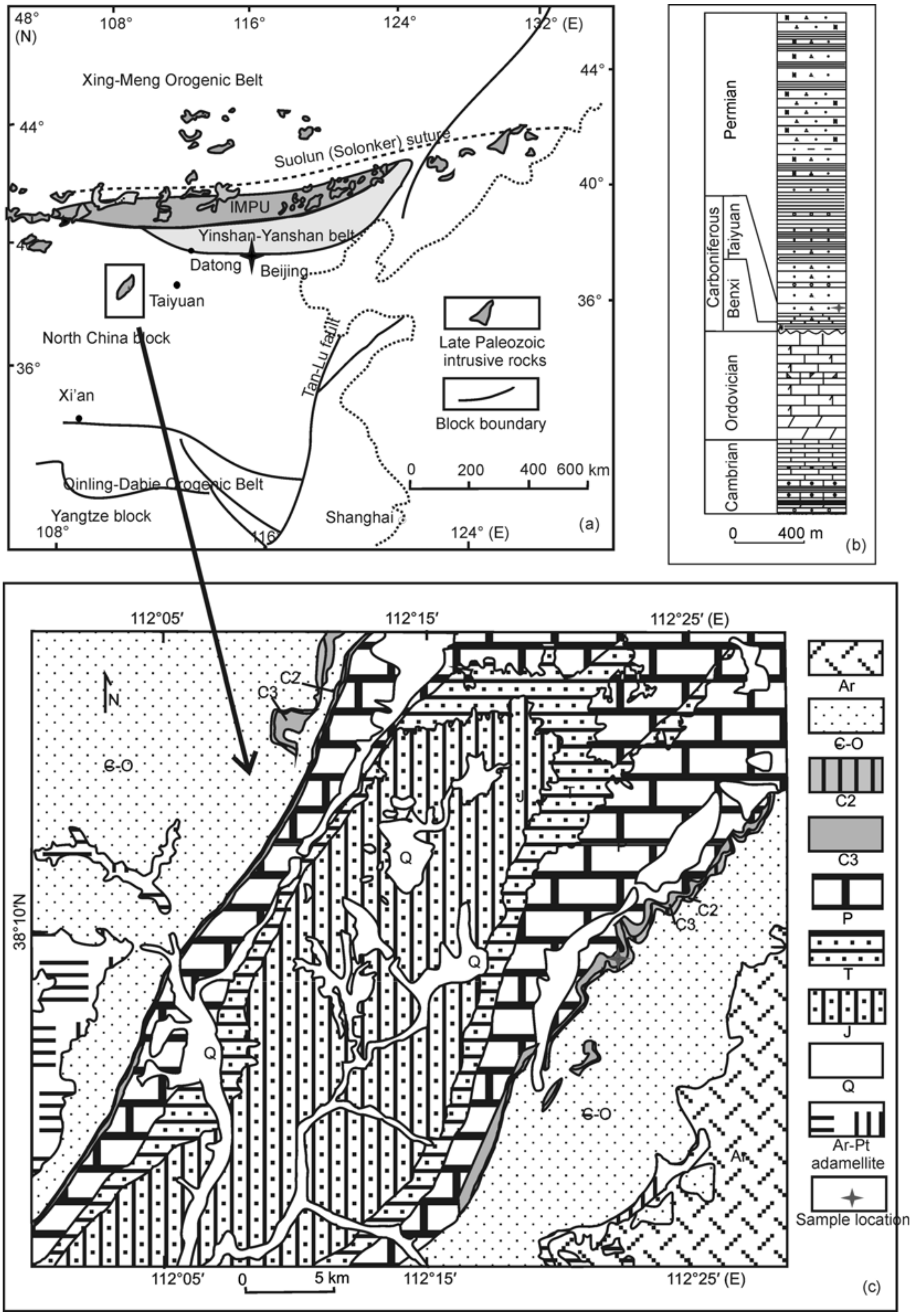

Figure 1 (a) Distribution of late Paleozoic granitoid intrusions; (b) Paleozoic stratigraphy of the Ningwu-Jingle basin; (c) geological map of Ningwu-Jingle basin.

gram (ver.4.0) was used for raw data reduction and age calculation, and the common-Pb correction used the method described by Andersen[37]. The age calculations and plotting of concordia diagrams were made using ISOPLOT (ver3.0). Detailed procedures are similar to those described by Yuan et al.[38].

In situ Hf isotopic analyses were carried out on the dated spots of young zircons using the Neptune MC-

ICPMS, equipped with a 193 nm laser, at the Institute of Geology and Geophysics, Chinese Academy of Sciences in Beijing, China. During analyses, spot sizes of 40 μm, with a laser repetition rate of 8 Hz at 100 mJ, were used. The detailed analytical technique and data correction procedure are described in Wu et al.[39]. During analyses, the $^{176}Hf/^{177}Hf$ and $^{176}Lu/^{177}Hf$ ratios of the standard zircon (91500) were 0.282289 ± 4 ($2\sigma_n$, n = 42) and 0.00029, similar to the low peaks of $^{176}Hf/^{177}Hf$ ratios of 0.282284 ± 22 measured using the laser method.

3 U-Pb age and Hf isotopes of detrital zircons

Eighty randomly selected grains of zircons were analyzed for U-Pb ages using LA-MC-ICPMS (Figure 2). Among them, six analyses are discarded because of low data acquisition. We obtained 74 U-Pb ages of 74 zircon grains, of which 72 ages are at the 90% confidence level. The result is shown in Table 1. Because of the low content of radiogenic Pb and the uncertainty associated with common Pb correction, the $^{207}Pb/^{206}Pb$ age is used for samples with ages greater than 1000 Ma and the $^{206}Pb/^{238}U$ age is used for samples whose age is younger than 1000 Ma[40]. Seventy-four ages are divided into three groups: 303—320 Ma (6 grains), 1631—2194 Ma (37 grains, peaked at 1850 Ma), 2318—2646 Ma (29 grains, peaked at 2500 Ma). All zircons have very high Th/U ratios, of which only 10 analyses are lower than 0.4 with ages ranging from 1820 to 2613 Ma ($^{207}Pb/^{206}Pb$ apparent age), while the other 64 analyses range from 0.4 to 2.01, indicating a magmatic origin although some zircons experienced Pb loss as a consequence of geological processes[17].

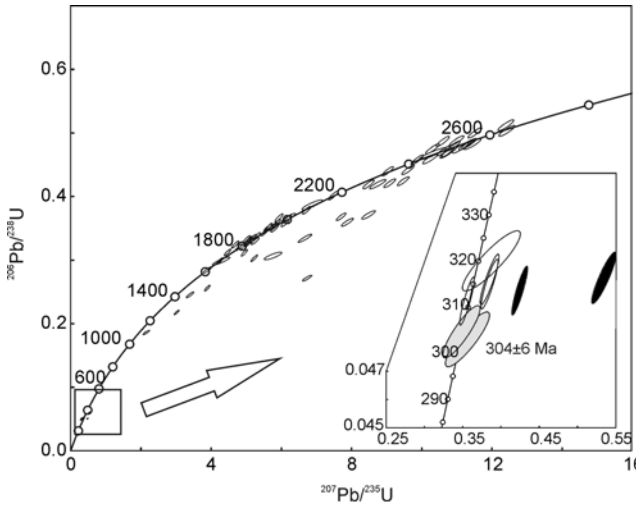

Figure 2 Detrital zircon U-Pb concordia age diagrams.

Table 1 LA-MC-ICPMS U-Pb dating results of detrital zircons of the Taiyuan Formation of Ningwu-Jingle basin

Spots	Element (ppm)		Th/U	Isotopic ratios (1σ)			r	Apparent age (Ma)		
	U	Th		$^{207}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$		$^{207}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$
N-8-01	374	85	0.23	0.1112 ± 12	4.921 ± 57	0.3209 ± 35	0.90	1820 ± 9	1806 ± 10	1794 ± 17
N-8-02	680	156	0.23	0.1162 ± 13	4.976 ± 57	0.3106 ± 34	0.90	1899 ± 9	1815 ± 10	1743 ± 17
N-8-03	517	153	0.30	0.1168 ± 13	5.662 ± 65	0.3517 ± 39	0.90	1907 ± 9	1926 ± 10	1943 ± 18
N-8-04	174	115	0.66	0.1046 ± 12	4.299 ± 51	0.2982 ± 33	0.90	1707 ± 10	1693 ± 10	1682 ± 16
N-8-05	125	189	1.52	0.1244 ± 14	6.133 ± 73	0.3577 ± 40	0.90	2020 ± 9	1995 ± 10	1971 ± 19
N-8-06	66	35	0.54	0.1516 ± 32	8.752 ± 154	0.4186 ± 50	0.91	2364 ± 37	2313 ± 16	2254 ± 23
N-8-07	120	121	1.01	0.1133 ± 13	5.225 ± 63	0.3344 ± 37	0.90	1853 ± 10	1857 ± 10	1860 ± 18
N-8-08	182	221	1.21	0.1148 ± 13	5.335 ± 63	0.3372 ± 37	0.90	1876 ± 10	1875 ± 10	1873 ± 18
N-8-09	18	15	0.86	0.1690 ± 22	11.09 ± 15	0.4759 ± 55	0.90	2548 ± 10	2531 ± 13	2509 ± 24
N-8-10	193	286	1.48	0.07696 ± 154	0.5338 ± 106	0.05030 ± 60	0.90	1120 ± 22	434 ± 7	316 ± 4
N-8-11	152	112	0.73	0.1233 ± 30	6.222 ± 130	0.3661 ± 44	0.91	2004 ± 44	2008 ± 18	2011 ± 21
N-8-12	153	119	0.78	0.1650 ± 18	10.90 ± 13	0.4787 ± 53	0.90	2508 ± 9	2514 ± 11	2521 ± 23
N-8-13	43	22	0.52	0.1200 ± 15	5.823 ± 78	0.3520 ± 40	0.90	1956 ± 11	1950 ± 12	1944 ± 19
N-8-14	104	150	1.44	0.1602 ± 45	10.30 ± 26	0.4664 ± 62	0.93	2458 ± 49	2462 ± 23	2468 ± 27
N-8-15	36	12	0.33	0.1621 ± 30	10.25 ± 15	0.4587 ± 52	0.91	2477 ± 31	2458 ± 13	2434 ± 23
N-8-16	172	204	1.19	0.1699 ± 18	11.26 ± 13	0.4805 ± 53	0.90	2557 ± 9	2545 ± 11	2529 ± 23
N-8-17	27	26	0.96	0.1665 ± 23	8.497 ± 122	0.3701 ± 43	0.90	2523 ± 11	2286 ± 13	2030 ± 20
N-8-18	141	79	0.56	0.1660 ± 18	10.71 ± 12	0.4679 ± 52	0.90	2518 ± 9	2498 ± 11	2474 ± 23
N-8-19	291	42	0.14	0.1116 ± 19	3.927 ± 53	0.2553 ± 28	0.90	1825 ± 32	1619 ± 11	1466 ± 14
N-8-20	40	19	0.47	0.1018 ± 24	3.436 ± 69	0.2448 ± 29	0.90	1657 ± 44	1513 ± 16	1412 ± 15
N-8-21	1125	893	0.79	0.1374 ± 43	5.788 ± 163	0.3056 ± 40	0.85	2194 ± 55	1945 ± 24	1719 ± 19
N-8-22	93	109	1.17	0.1566 ± 17	9.867 ± 117	0.4569 ± 51	0.90	2420 ± 9	2422 ± 11	2426 ± 22
N-8-23	407	148	0.36	0.1493 ± 16	9.035 ± 104	0.4390 ± 48	0.90	2337 ± 9	2342 ± 11	2346 ± 22

(*To be continued on the next page*)

(*Continued*)

Spots	Element (ppm)		Th/U	Isotopic ratios (1σ)			r	Apparent age (Ma)		
	U	Th		$^{207}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$		$^{207}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$
N- 8-24	49	79	1.60	0.1118 ± 14	5.106 ± 67	0.3312 ± 37	0.90	1829 ± 11	1837 ± 11	1844 ± 18
N-8-26	217	163	0.75	0.1582 ± 17	9.613 ± 111	0.4408 ± 49	0.90	2436 ± 9	2398 ± 11	2354 ± 22
N-8-27	150	125	0.84	0.05558 ± 106	0.3838 ± 74	0.05008 ± 58	0.90	436 ± 23	330 ± 5	315 ± 4
N-8-28	275	204	0.74	0.1624 ± 18	9.477 ± 111	0.4234 ± 47	0.90	2480 ± 9	2385 ± 11	2276 ± 21
N-8-29	83	47	0.56	0.1792 ± 20	12.42 ± 15	0.5025 ± 56	0.90	2646 ± 9	2637 ± 11	2624 ± 24
N-8-30	37	15	0.41	0.1664 ± 20	10.78 ± 14	0.4701 ± 53	0.90	2521 ± 9	2505 ± 12	2484 ± 23
N-8-31	286	23	0.08	0.1525 ± 24	7.726 ± 90	0.3676 ± 40	0.89	2374 ± 28	2200 ± 10	2018 ± 19
N-8-32	19	17	0.87	0.1295 ± 40	6.894 ± 190	0.3863 ± 51	0.90	2090 ± 55	2098 ± 24	2105 ± 24
N-8-33	309	348	1.13	0.05200 ± 250	0.3470 ± 161	0.04840 ± 61	0.88	285 ± 113	302 ± 12	305 ± 4
N-8-34	97	66	0.68	0.1121 ± 13	5.099 ± 62	0.3300 ± 37	0.90	1833 ± 10	1836 ± 10	1838 ± 18
N-8-35	143	254	1.78	0.1576 ± 18	10.30 ± 13	0.4743 ± 53	0.90	2430 ± 9	2462 ± 11	2502 ± 23
N-8-36	329	375	1.14	0.05191 ± 92	0.3541 ± 63	0.04948 ± 56	0.90	281 ± 21	308 ± 5	311 ± 3
N-8-37	79	81	1.02	0.1214 ± 14	5.842 ± 72	0.3491 ± 39	0.90	1977 ± 10	1953 ± 11	1930 ± 19
N-8-38	796	393	0.49	0.1260 ± 14	5.249 ± 62	0.3022 ± 33	0.90	2042 ± 9	1861 ± 10	1702 ± 16
N-8-39	118	223	1.89	0.1808 ± 22	6.753 ± 85	0.2709 ± 30	0.90	2660 ± 9	2080 ± 11	1545 ± 15
N-8-40	249	202	0.81	0.1672 ± 18	11.51 ± 13	0.4993 ± 55	0.90	2530 ± 9	2565 ± 11	2611 ± 24
N-8-41	152	33	0.21	0.1357 ± 16	7.500 ± 91	0.4009 ± 45	0.90	2173 ± 9	2173 ± 11	2173 ± 20
N-8-42	52	35	0.66	0.1056 ± 14	4.715 ± 66	0.3239 ± 37	0.90	1724 ± 12	1770 ± 12	1809 ± 18
N-8-43	514	654	1.27	0.1571 ± 17	9.097 ± 107	0.4200 ± 46	0.90	2424 ± 9	2348 ± 11	2261 ± 21
N-8-45	42	34	0.83	0.1021 ± 16	3.055 ± 48	0.2171 ± 25	0.90	1662 ± 14	1421 ± 12	1266 ± 13
N-8-46	1060	890	0.84	0.1455 ± 33	6.690 ± 128	0.3336 ± 40	0.92	2293 ± 40	2071 ± 17	1856 ± 19
N-8-47	49	44	0.89	0.1190 ± 15	5.769 ± 75	0.3516 ± 40	0.90	1942 ± 10	1942 ± 11	1942 ± 19
N-8-48	138	120	0.87	0.1583 ± 18	10.60 ± 13	0.4858 ± 54	0.90	2437 ± 9	2489 ± 11	2553 ± 23
N-8-49	31	27	0.87	0.1047 ± 15	4.496 ± 67	0.3114 ± 36	0.90	1710 ± 13	1730 ± 12	1748 ± 18
N-8-50	244	81	0.33	0.1757 ± 20	12.39 ± 15	0.5113 ± 57	0.90	2613 ± 9	2634 ± 11	2662 ± 24
N-8-51	209	154	0.74	0.1235 ± 14	6.200 ± 75	0.3641 ± 40	0.90	2007 ± 10	2004 ± 11	2002 ± 19
N-8-52	172	160	0.93	0.1296 ± 15	6.745 ± 84	0.3776 ± 42	0.90	2092 ± 10	2079 ± 11	2065 ± 20
N-8-54	200	126	0.63	0.1476 ± 17	8.504 ± 103	0.4180 ± 46	0.90	2318 ± 9	2286 ± 11	2251 ± 21
N-8-55	105	78	0.74	0.0859 ± 26	2.196 ± 61	0.1853 ± 23	0.90	1336 ± 60	1180 ± 19	1096 ± 12
N-8-57	216	87	0.40	0.1175 ± 14	5.550 ± 68	0.3425 ± 38	0.90	1919 ± 10	1908 ± 11	1899 ± 18
N-8-58	182	346	1.90	0.05503 ± 366	0.3862 ± 251	0.05090 ± 70	0.89	413 ± 153	332 ± 18	320 ± 4
N-8-59	54	63	1.17	0.1095 ± 15	4.820 ± 67	0.3193 ± 36	0.90	1791 ± 11	1788 ± 12	1786 ± 18
N-8-60	243	221	0.91	0.1705 ± 19	11.34 ± 14	0.4824 ± 54	0.90	2562 ± 9	2551 ± 11	2538 ± 23
N-8-61	43	52	1.22	0.1131 ± 15	5.078 ± 69	0.3256 ± 37	0.90	1850 ± 11	1832 ± 12	1817 ± 18
N-8-62	83	102	1.22	0.05544 ± 118	0.3840 ± 81	0.0502 ± 6	0.90	430 ± 27	330 ± 6	316 ± 4
N-8-63	44	29	0.65	0.07014 ± 250	0.5738 ± 201	0.0593 ± 8	0.90	932 ± 49	460 ± 13	372 ± 5
N-8-64	33	30	0.90	0.1195 ± 16	5.882 ± 82	0.3571 ± 41	0.90	1948 ± 11	1959 ± 12	1969 ± 19
N-8-65	201	136	0.67	0.06161 ± 98	0.4235 ± 69	0.0499 ± 6	0.90	661 ± 17	359 ± 5	314 ± 3
N-8-66	147	83	0.57	0.1101 ± 13	5.044 ± 63	0.3322 ± 37	0.90	1802 ± 10	1827 ± 11	1849 ± 18
N-8-67	42	52	1.26	0.1165 ± 16	5.292 ± 74	0.3295 ± 38	0.90	1903 ± 11	1868 ± 12	1836 ± 18
N-8-68	41	64	1.56	0.1120 ± 15	5.064 ± 70	0.3280 ± 37	0.90	1832 ± 11	1830 ± 12	1829 ± 18
N-8-69	69	104	1.51	0.1635 ± 20	10.62 ± 13	0.4713 ± 53	0.90	2492 ± 9	2491 ± 12	2489 ± 23
N-8-70	163	90	0.55	0.1004 ± 23	3.930 ± 78	0.2840 ± 33	0.91	1631 ± 44	1620 ± 16	1612 ± 17
N-8-71	53	56	1.05	0.1130 ± 15	5.099 ± 69	0.3272 ± 37	0.90	1849 ± 11	1836 ± 11	1825 ± 18
N-8-72	147	87	0.59	0.1639 ± 19	10.00 ± 14	0.4866 ± 54	0.90	2496 ± 9	2523 ± 12	2556 ± 24
N-8-73	377	145	0.38	0.1180 ± 14	5.954 ± 74	0.3659 ± 41	0.90	1927 ± 10	1969 ± 11	2010 ± 19
N-8-74	54	75	1.38	0.1052 ± 42	4.319 ± 163	0.2979 ± 41	0.91	1717 ± 76	1697 ± 31	1681 ± 21
N-8-75	70	76	1.09	0.05346 ± 297	0.3548 ± 191	0.04813 ± 64	0.88	348 ± 129	308 ± 14	303 ± 4
N-8-76	100	201	2.01	0.1664 ± 20	10.73 ± 14	0.4676 ± 52	0.90	2522 ± 9	2500 ± 12	2473 ± 23
N-8-77	42	46	1.10	0.1596 ± 21	7.892 ± 108	0.3586 ± 41	0.90	2452 ± 10	2219 ± 12	1976 ± 19
N-8-78	435	123	0.28	0.1723 ± 30	11.44 ± 16	0.4814 ± 54	0.91	2580 ± 30	2559 ± 13	2534 ± 23
N-8-79	129	115	0.89	0.1169 ± 14	5.653 ± 72	0.3508 ± 39	0.90	1909 ± 10	1924 ± 11	1938 ± 19
N-8-80	105	193	1.83	0.1143 ± 14	5.218 ± 68	0.3311 ± 37	0.90	1869 ± 10	1856 ± 11	1844 ± 18

In situ Lu-Hf isotope analyses were carried out on seven grains of young zircons, of which five grains belonging to Group 1 and two other grains (N-8-10; N-8-65) are discordant. The results yield $^{176}Hf/^{177}Hf$ ratios from 0.281725 to 0.282239 and corresponding $\varepsilon_{Hf}(t)$ values from −12.4 to −30.3. The Hf isotopic model ages (T_{DM}) for these zircons range from 1.43 to 2.16 Ga (Table 2).

Initial Hf isotope ratios are calculated with reference to the chondritic reservoir at the time of magma crystallization, a decay constant for ^{176}Lu of 1.867×10^{-11} a^{-1} [41] and chondritic ratios of $^{176}Hf/^{177}Hf$ (= 0.282772) and $^{176}Lu/^{177}Hf$ (= 0.0332)[42] were adopted. Single-stage model ages (T_{DM}) are calculated using the measured $^{176}Lu/^{177}Hf$ ratios, referring to a model depleted mantle with a present-day $^{176}Hf/^{177}Hf$ ratio of 0.28325 and $^{176}Lu/^{177}Hf$ = 0.0384[43]. The crystallization ages are the single zircon U-Pb ages analyzed above.

4 Provenance analyses of detrital zircons

Yang et al.[19] analyzed the provenance of detrital zircons from the Upper Carboniferous Taiyuan Formation sedimentary rocks in the Xishan basin near Beijing. Their detrital zircons from the Xishan basin are characterized by three groups in terms of age distribution: 407—304 Ma (12 grains, $\varepsilon_{Hf}(t)$ values of −24.0—−9.9), 1912—1774 Ma (8 grains, peaked at 1850 Ma) and 2530—2399 Ma (21 grains, peaked at 2500 Ma). Therefore, in general, the U-Pb age spectra and Hf isotopic data of detrital zircons from the Taiyuan Formation in the Ningwu-Jingle basin are similar to those in the Xishan basin. Yang et al.[19] proposed that the sediments of the Taiyuan Formation were derived from the northern margin of the NCC, but have not provided detailed reasoning. Here, a detailed analysis is given for the source provenance of Late Carboniferous strata in the Ningwu-Jingle basin and the Xishan basin, in the light of recent research progress made in the northern margin of the NCC.

Data are from refs. [12, 13, 19, 44, 45]. Some Sm-Nd and Rb-Sr ages[44] were adopted for Qingling-Dabie data statistics.

The hinterland of the NCC was stable during the Paleozoic, except for a few tectonic and magmatic activities localized on the northern and southern margin of the NCC. The North Qinling Ocean closed in the Early Paleozoic, and an Early Paleozoic volcanic arc was formed along the area from Qinling to Dabie at the southern margin of the NCC[23,24,44,45]. Therefore many scholars regarded the Early Paleozoic zircon U-Pb ages as the provenance diagnostic for the southern margin of the NCC[16,22,45−47]. No Early Paleozoic U-Pb age has been found during this study (Figure 3), ruling out the possibility of the southern margin of the NCC as source of the Ningwu-Jingle sedimentary basin. This leads us to focus on the potential provenance links to the northern margin of the NCC and the XMOB. According to *in situ* U-Pb ages and Hf isotope analyses, igneous zircons of the northern margin of the NCC are characterized by three groups[19]: (1) U-Pb ages of 2.6 to 2.4 Ga, $\varepsilon_{Hf}(t)$ values of −1.5 to 8.7; (2) U-Pb ages of 1.9 to 1.7 Ga, $\varepsilon_{Hf}(t)$ values of −10 to 2; and (3) U-Pb ages of 390 to 107 Ma, $\varepsilon_{Hf}(t)$ from −3.8 to −22.8. In sharp contrast, U-Pb ages of zircons from the XMOB igneous rocks are all Phanerozoic, ranging from 531 to 111 Ma, with $\varepsilon_{Hf}(t)$ values of −4.2—16.3[25−30].

U-Pb ages of Group 1 detrital zircons (303—320 Ma) of the Taiyuan Formation are mainly Carboniferous igneous zircons. $\varepsilon_{Hf}(t)$ values of zircons range from −12.4 to −30.3. In terms of crystallization age and isotope composition, these zircons are very similar to the known Carboniferous igneous zircons of the Inner Mongolia Paleo-uplift (IMPU) in the northern margin of the NCC, but are very different from those of the Xing-Meng Orogenic Belt (Figure 4). In addition, Carboniferous igneous rocks, of which U-Pb ages range from 324 to

Table 2 LA-MC-ICPMS Lu-Hf isotope analyses of detrital zircons from the Taiyuan Formation in the Ningwu-Jingle basin

Spots	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	± (2σ)	$\varepsilon_{Hf}(t)$	± (2σ)	T_{DM}(Ma)	± (2σ)
N-8-10	0.025789	0.000943	0.282052	0.000024	−18.7	0.9	1.69	0.03
N-8-27	0.031583	0.001194	0.282068	0.000017	−18.2	0.6	1.68	0.02
N-8-33	0.049448	0.001807	0.282175	0.000022	−14.8	0.8	1.55	0.03
N-8-36	0.041161	0.001589	0.282057	0.000020	−18.8	0.7	1.71	0.03
N-8-58	0.034813	0.001339	0.281725	0.000019	−30.3	0.7	2.16	0.03
N-8-65	0.023994	0.000970	0.282041	0.000019	−19.1	0.7	1.70	0.03
N-8-75	0.031977	0.001147	0.282239	0.000017	−12.4	0.6	1.43	0.02

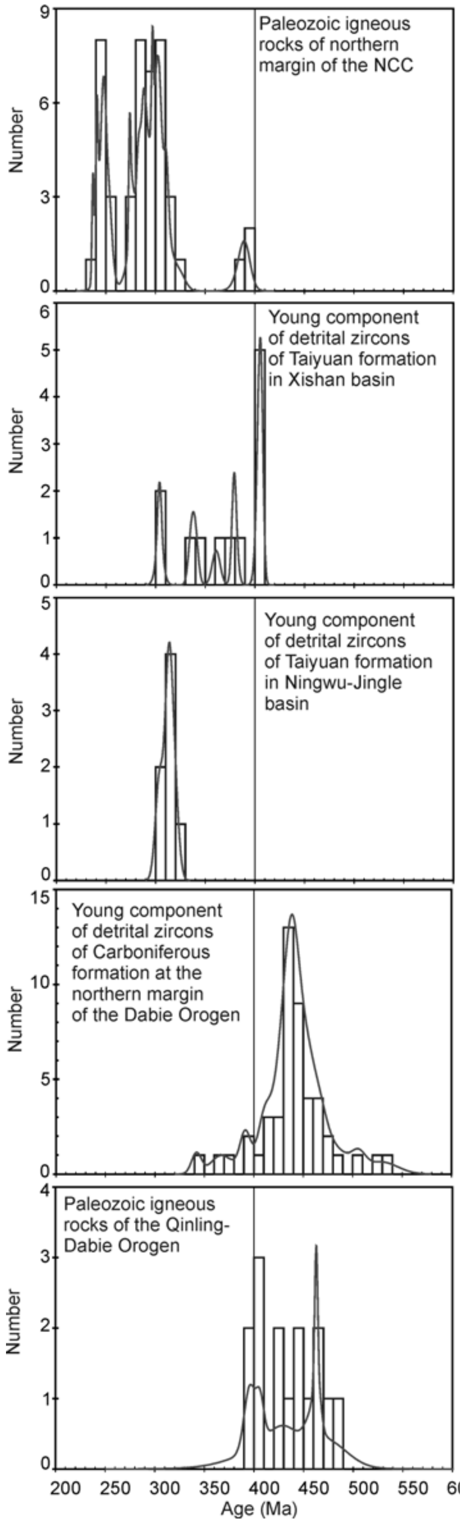

Figure 3 Age histogram of Carboniferous igneous zircons around NCC and detrital zircons of sedimentary formation. Data are from refs. [12, 13, 19, 48, 49]. Some Sm-Nd and Rb-Sr ages[48] were adopted for Qingling- Dabie data statistics.

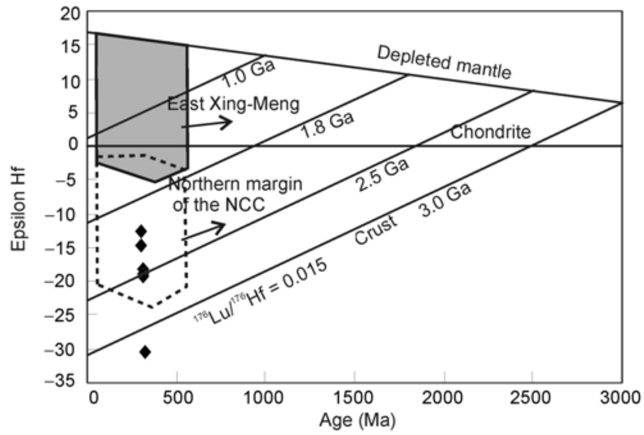

Figure 4 Hf isotopes of detrital zircons of the Taiyuan Formation in the Ningwu-Jingle basin.

300 Ma[11,13,34], are mainly distributed in Longhua, Daguangding, Boluonuo, Jianping, Dongwanzi, and other regions in the IMPU (Figure 1(a)), whereas no occurrence has been reported in the Yanshan thrust-and-fold belt. It is therefore inferred that the detrital zircons of Group 1 mainly came from the IMPU. Detrital zircons of Group 2 (1631—2194 Ma) and Group 3 (2318—2646 Ma) are reflective of the provenance from the NCC basement[19]. Some sedimentary evidence indicated that the Yanshan thrust-and-fold belt was a subsidence area and the IMPU was an erosion area during the Paleozoic. Mesoproterozoic-Paleozoic sedimentary rocks are widely distributed in the Yanshan thrust-and-fold belt but are absent in the IMPU except for some Mesoproterozoic sedimentary rocks distributed in a narrow belt along the Fengning-Longhua fault. This suggests that the detrital zircons of Group 1 and 2 may have mainly been derived from the denudation of the IMPU basement, although the possibility that a small amount of source came from the denudation of the NCC hinterland basement and the recycling of sediments prior to the Taiyuan Formation cannot be fully precluded. We thus conclude that the sediments of the Taiyuan Formation of the Upper Carboniferous from the Ningwu-Jingle basin were mainly derived from the IMPU on the northern margin of the NCC, as was the Xishan basin. In addition, both the provenance of sedimentary rocks in the northern Ordos Basin from the Yinshan paleo-land area during the Late Paleozoic[50,51] and the north to south trending paleocurrent in the area from Baode County of Shanxi Province to Fugu County of Shaanxi Province[52] provide important evidence for the transport of materials from the IMPU for the area from the Ningwu-Jingle basin to the Xishan basin during the Late Paleozoic.

5 Implications for the evolution of the NCC

There are various views concerning possible mechanisms of lithosphere thinning of the NCC related to craton destruction[1,2,7,53,54]. One major reason for such a wide variety of views is that the superficial responses to deep cratonic destruction are poorly defined, and consequently processes related to cratonic destruction cannot be constrained by superficial geology. Although the Late Carboniferous is much earlier than the currently proposed destruction timing (i.e., Late Triassic[55,56], Jurassic and Cretaceous[53,54,57]), the characterization of superficial geology prior to craton destruction is of great importance for studying the processes of craton destruction.

Lithologic and sedimentologic studies of Late Paleozoic coal-bearing strata of the NCC show that volcanic pyroclastic layers are commonly distributed at the top and bottom of Late Paleozoic coal seam or within its parting clay[58−62]. For example, several volcanic pyroclastic layers are intercalated in Late Paleozoic coal-bearing strata in the central and northern parts of Shanxi Province, and the number of volcanic layers decreases from 7 to 5 from north to south. Their lithological characters change from typical tuffs to sediment-tuff and tuffaceous sedimentary rocks[63], suggesting that the source of volcanics from the northern margin of the NCC. It appears that the NCC was tectonically active in the Late Paleozoic and volcanisms may have taken place. Recent discoveries of Late Paleozoic granitoid plutons in the IMPU[13] and the tuff[12] from western Beijing indicate that the IMPU may have activated in the Late Paleozoic. Much geological evidence for this Late Paleozoic activation of the NCC has been destroyed due to the uplift and exhumation processes of the IMPU since the Late Paleozoic. Based on the provenance analyses of the Taiyuan Formation from the Ningwu-Jingle basin and the Xishan basin, many IMPU sources, which may have resulted from the denudation of the Abdean-type continental marginal arc in the IMPU, are identified in Late Carboniferous sedimentary rocks from the hinterland of the craton, providing important superficial geological evidence for the activation of the northern margin of the NCC. The minimum U-Pb ages of detrital zircons from the Taiyuan Formation from the Ningwu-Jingle basin and the Xishan basin are respectively 304 ± 6 Ma and 304 ± 4 Ma, virtually identical to the depositional ages of the Formation, suggestive of a rapid uplift and extensive magmatism in the IMPU. Because the Xishan basin is located close to the northern margin of the NCC, it might be expected to accumulate more sedimentary source from the IMPU compared to the Ningwu-Jingle basin. This is reflected by a higher proportion of relatively young age detrital zircons from the Xishan basin (24%) than from the Ningwu-Jingle basin (9%).

In addition, the ages of detrital zircons extracted from Carboniferous sedimentary rocks in the northern margin of the Dabie Mountains are concentrated between 400 and 480 Ma[45]. The absence of Late Paleozoic ages suggests that the southern margin of the NCC was relatively stable during the Late Carboniferous without major tectonic and magmatic activities. Based on the age analyses of detrital zircons from Carboniferous sedimentary rocks from the northern and southern margins of the NCC, it is clear that Carboniferous tectonic and magmatic activities occurred mainly along the northern margin of the NCC. It appears that the northern margin of the NCC was activated at a time not later than Late Carboniferous.

6 Conclusions

(1) The ages and Hf isotopes of young detrital zircons (303−320 Ma) from the Upper Carboniferous Taiyuan Formation in Ningwu-Jingle basin of Shanxi Province show a strong resemblance to those of Carboniferous igneous zircons from the IMPU.

(2) As a result of the Central Asian Orogenic process, the northern margin of the NCC had already been activated no later than the Late Carboniferous. The strong tectonic and magmatic activities in the IMPU during the Late Paleozoic supplied sedimentary source for the area from the Ningwu-Jingle basin to the Xishan basin.

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