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华北克拉通南缘五佛山群沉积时代和物源区分析: 碎屑锆石 U-Pb 年龄和 Hf 同位素证据

胡国辉[1,2], 赵太平[1*,3], 周艳艳[1,2], 杨 阳[1,2]

(1. 中国科学院 广州地球化学研究所, 广东 广州 510640; 2. 中国科学院 研究生院, 北京 100049; 3. 西北大学 大陆动力学国家重点实验室, 陕西 西安 710069)

摘 要: 河南嵩山地区位于华北克拉通南缘, 其早前寒武纪结晶基底主要由新太古代登封群表壳岩、TTG 质片麻岩和古元古代嵩山群石英岩, 以及新太古代-古元古代的花岗质岩石组成。五佛山群角度不整合覆盖于登封群和嵩山群之上, 主要由石英砂岩组成, 夹少量的粉砂质页岩和薄层灰岩, 为该地区太古宙-古元古代结晶基底之上分布广泛的第一沉积盖层。探讨其沉积时代和物质来源, 对揭示华北克拉通南缘前寒武纪地壳演化过程具有重要意义, 并可为华北南缘前寒武纪地层框架的建立和对比提供依据。本文对五佛山群底部马鞍山组两个石英砂岩样品的碎屑锆石进行 LA-ICP-MS U-Pb 年龄测定, 获得最年轻的 $^{207}Pb/^{206}Pb$ 年龄分别为(1732±11) Ma 和(1655±22) Ma, 说明五佛山群形成时代的下限为古元古代晚期, 与华北克拉通南缘熊耳群火山-沉积岩系之后的其他沉积盖层年代相当。五佛山群碎屑锆石 $^{207}Pb/^{206}Pb$ 年龄范围为 2816~1655 Ma, 主要集中于 2100~1800 Ma 之间(约占 60%), 年龄主峰值为(1.93±0.10) Ga, 部分年龄分布于 2500~2100 Ma 之间(约占 24%), 说明其沉积物质主要来源于古元古代的地质体, 相比华北克拉通其他地区同时代的沉积地层碎屑锆石年代学研究结果, 本区来自太古宙的物源极少。五佛山群马鞍山组碎屑锆石的 U-Pb 年龄反映了嵩山地区在 1.93 Ga 左右发生过重要的构造-热事件, 与华北克拉通古元古代中期发生的变质作用时间(约 1.91 Ga)一致。碎屑锆石 $\varepsilon_{Hf}(t)$值为–14.3~4.6, Hf 的两阶段模式年龄分布于 2363~3672 Ma 之间, 明显大于其 $^{207}Pb/^{206}Pb$ 年龄, 大部分锆石的 Hf 同位素组成集中于 2.50 Ga 和 2.80 Ga 地壳演化线区域内, 揭示了新太古代为华北克拉通南缘重要的陆壳生长期。

关键词: 五佛山群; 碎屑锆石; U-Pb 年龄; 源区; 华北克拉通

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Depositional age and provenance of the Wufoshan Group in the southern margin of the North China Craton: Evidence from detrital zircon U-Pb ages and Hf isotopic compositions

HU Guo-hui[1,2], ZHAO Tai-ping[1*,3], ZHOU Yan-yan[1,2] and YANG Yang[1,2]

1. *Guangzhou Institute of Geochemistry*, *Chinese Academy of Sciences*, *Guangzhou* 510640, *China*;
2. *Graduate University of Chinese Academy of Sciences*, *Beijing* 100049, *China*;
3. *State Key Laboratory of Continental Dynamics*, *Northwest University*, *Xi'an* 710069, *China*

Abstract: Early Precambrian crystalline basement in the Songshan region, the south margin of the North China Craton (NNC), mainly consists of the Neoarchean Dengfeng Group TTG gneiss, Paleoproterozoic Songshan Group quartzite and Neoarchean to Paleoproterozoic granitic rocks. The Wufoshan Group, covering on the Dengfeng Group and Songshan Group with angular unconformity, is mainly composed of quartz sandstone and minor silty shale and thin layer of limestone. The depositional age and provenance of the Wufoshan Group, the oldest sedimentary cover on the Archean-Paleoproterozoic crystalline basement, could provide constraints on the

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作者简介: 胡国辉(1984–), 男, 博士研究生, 岩石地球化学专业。E-mail: huguohui1984@126.com

* 通讯作者**(Corresponding author):** ZHAO Tai-ping, E-mail: tpzhao@gig.ac.cn, Tel: +86-20-85290231

classification of the Proterozoic stratum and the Precambrian crustal evolution of the northern margin of the NCC. This study reports LA-ICP-MS U-Pb ages and Hf isotope compositions of the detrital zircon from two quartz sandstones of the Ma'anshan Formation at the bottom of the Wufoshan Group. The youngest $^{207}Pb/^{206}Pb$ ages are (1732±11) Ma and (1655±22) Ma, respectively, contemporary with the Mesoproterozoic sedimentary stratum formed after Xiong'er Group volcanic-sedimentary rocks. The $^{207}Pb/^{206}Pb$ ages of the detrital zircons range from 2816 Ma to 1655 Ma with 60% between 2100 Ma and 1800 Ma and 24% between 2500 Ma and 2100 Ma, indicating that sedimentary materials mainly sourced from Paleoproterozoic geologic bodies. Combined with detrital zircon studies on sedimentary rocks from other regions of the NCC, the Archean-Paleoproterozoic crystalline basement is the main source of the Mesoproterozoic detrital materials of the NCC. The $^{207}Pb/^{206}Pb$ ages peak at (1.93±0.10) Ga, indicate significant early Precambrain tectonic-thermal events in the Songshan region, in conformity with Paleoproterozoic metamorphism ages (~1.91 Ga). All detrital zircons have obvious negative to moderately positive $\varepsilon_{Hf}(t)$ values from –14.3 to 4.6, with Hf model ages (T_{DM}^{C}) ranging from 3672 Ma to 2363 Ma. Most T_{DM}^{C} model ages are between 2.80 Ga and 2.50 Ga evolution lines of crust, indicating that Neoarchean is the main crustal growth period of the southern margin of the NCC.

Key words: Wufoshan Group; detrital zircon; U-Pb age; provenance; North China Craton

0　引　言

锆石具有较强的抗风化性和抗干扰性，在风化、剥蚀、搬运、沉积和成岩过程中保持稳定。由于锆石U-Th-Pb同位素体系具有较高的封闭温度[1–2]，在成岩过程和低级变质作用下受扰动较小，可以保持其形成时的特征。因此，在缺乏火山岩夹层和生物记录的前寒武纪沉积地层中，通常利用碎屑锆石最年轻的U-Pb同位素年龄来制约地层的最大沉积时代[3–7]；同时，根据大量的碎屑锆石年龄统计结果可以确定碎屑沉积岩的物质来源[8]、恢复区域古地理格局[9]和揭示陆壳演化历史[10]等。

华北克拉通太古宙-古元古代结晶基底之上不整合覆盖着大面积的中-新元古代沉积盖层，主要包括北部的狼山-渣尔泰山群和白云鄂博群[11–12]，中部和东部的长城系、蓟县系和青白口系[13–17]，南部的熊耳群火山-沉积岩系及其上的中-新元古代沉积地层[18–22]。嵩山地区是华北克拉通南缘前寒武系典型地层出露区之一，其早前寒武纪结晶基底主要由新太古界登封群TTG质片麻岩(2.60~2.50 Ga)[23–25]和古元古界早期嵩山群石英岩(2.45~2.00 Ga)[23,26]组成，之后开始发育稳定的沉积盖层。由于仅在局部地区发现有少量的古元古代晚期熊耳群火山-沉积地层，而五佛山群直接角度不整合覆盖于登封群和嵩山群之上。因此，五佛山群为嵩山地区太古宙-古元古代褶皱变质基底之上分布面积最大的第一沉积盖层，对它的研究对揭示华北克拉通结晶基底的性质及其构造-热事件具有重要意义。

前人的研究认为五佛山群从1400 Ma左右开始沉积[27]，微古植物组合特征也表明其形成于中-新元古代[18]，但缺乏精确的年龄资料。本文拟选择五佛山群底部的石英砂岩样品进行碎屑锆石LA-ICP-MS U-Pb年龄和Hf同位素分析，探讨其沉积时代和物质来源，为该地区中-新元古代沉积地层的划分和厘定提供依据，并与其他区域同时代的沉积地层进行对比，进而为分析讨论华北克拉通南缘早前寒武纪地壳演化历史提供制约。

1　区域地质背景

嵩山地区前寒武纪岩石序列发育较为完整(图 1)，主要有新太古界登封群表壳岩[19,23,24,28]、TTG 片麻岩(2.60~2.50 Ga)[19,23,24,28,29]、古元古界嵩山群(2.00~2.45 Ga)[23,26]、中-新元古界五佛山群[27]等。其中新太古界登封群、TTG 片麻岩、古元古界嵩山群和侵入其中的基性岩墙群以及花岗岩系列[30–31]共同构成嵩山地区前寒武纪结晶基底，沉积盖层主要由中-新元古界及之后的地层组成。空间上，新太古界登封群近南北向分布，产状近于直立，被古元古界嵩山群不整合覆盖；古元古界嵩山群主要由石英岩组成，也呈近南北向分布，被元古宇五佛山群不整合覆盖。新太古界 TTG 质片麻岩侵入登封群，并普遍被嵩山群、五佛山群和第四系覆盖。古元古代早

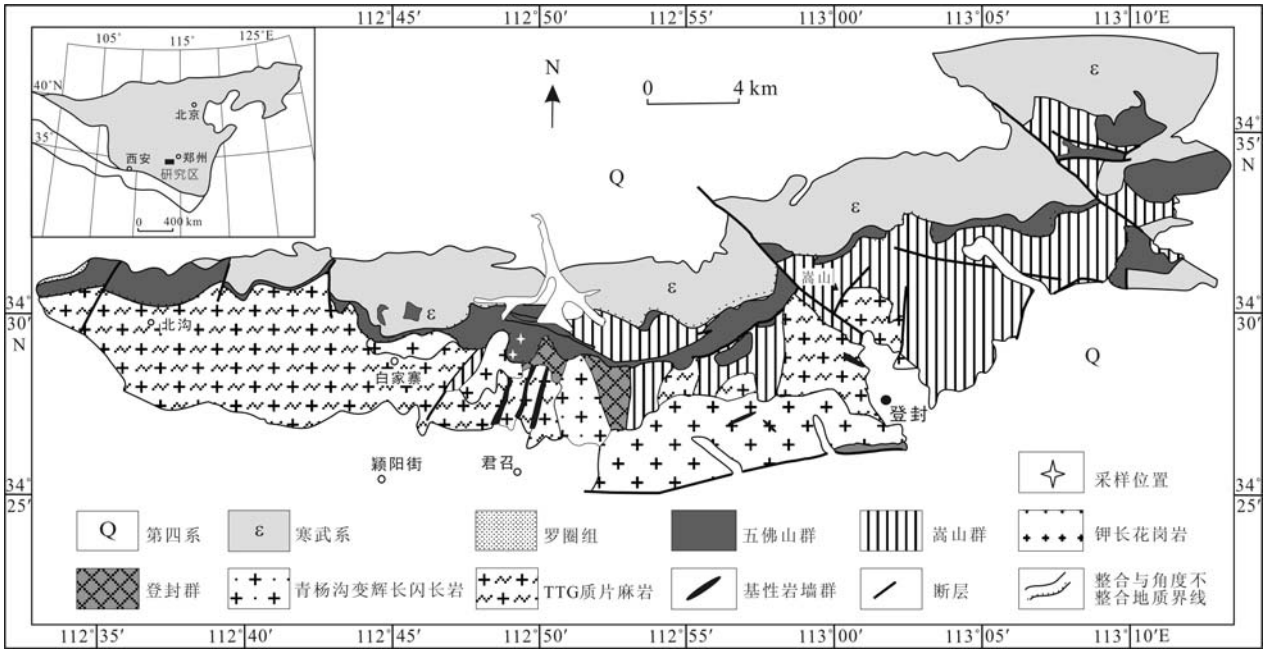

图1 华北克拉通南缘嵩山地区地质简图

Fig.1 Simplified geological map of Songshan region at the south margin of the North China Craton

期的路家沟钾长花岗岩侵入新太古界登封群和 TTG 片麻岩中，并被中-新元古界五佛山群不整合覆盖。古元古代晚期的石秤和白家寨钾长花岗岩均侵入 TTG 片麻岩中，前者侵入新太古界登封群和古元古界嵩山群中，后者被五佛山群不整合覆盖[31]。

嵩山地区五佛山群自下而上分为马鞍山组、葡峪组、骆驼畔组和何家寨组[32]，主要分布于玉寨山-五佛山北坡，以登封市少林寺-偃师市何家寨一带层序发育最为齐全，其他地区仅有下部层位马鞍山组出露。在嵩山西段兵马沟地区，五佛山群假整合于兵马沟组之上，局部地区则直接不整合覆盖于白家寨钾长花岗岩之上[31]。在登封城西北的马鞍山附近，直接角度不整合覆盖于新太古界登封群之上，在许多地方都存在底砾岩。在玉寨山北坡则直接角度不整合覆盖于古元古界嵩山群之上。五佛山群的上覆地层在不同地区也不尽相同。嵩山西段马鞍山组被震旦系罗圈组冰碛杂岩假整合覆盖；在少林寺-何家寨以及嵩山以东地区，五佛山群则被寒武系关口砂岩不整合覆盖。

2 样品采集与分析方法

本文用于碎屑锆石分析的样品WFS-1和WFS11均采自嵩山地区玉寨山-五佛山北坡马鞍山组。WFS11位于马鞍山组底部，接近马鞍山组与太古宙登封群角度不整合界线，WFS-1采自于马鞍山组上部。锆石的U-Pb同位素年代学和Hf同位素分析在中国科学院地质与地球物理研究所进行。

U-Pb同位素分析使用Agilent公司7500a型ICP-MS进行测试，Lu-Hf同位素测试使用德国Finnigan公司制造的Neptune型多接收电感耦合等离子体质谱(MC-ICP-MS)，加载德国Lamda Physik公司制造的Geolas193nm准分子激光取样系统。锆石Lu-Hf同位素分析和U-Pb定年的ICP-MS使用同一台激光剥蚀系统，对样品进行一次性剥蚀测试。所测锆石的粒径在100~250 μm之间，采用激光束直径为70 μm，剥蚀频率为10 Hz，能量密度为15 J/cm^2，剥蚀时间为27 s，剥蚀深度20~30 μm。详细的分析流程见文献[33]。

锆石的U-Pb同位素及U、Th数据处理使用Glitter 4.0软件[34]，U-Pb谐和图和加权平均年龄的计算及绘图用Isoplot 3.0软件[35]完成。数据标准化根据$^{179}Hf/^{177}Hf$ = 0.7325，质量歧视校正用指数法则进行，Yb和Lu的干扰校正取$^{176}Lu/^{175}Lu$ = 0.02655[36]和$^{176}Yb/^{172}Yb$ = 0.5887，而Yb分馏校正则根据$^{172}Yb/^{173}Yb$ = 1.35272用指数法则进行[33]。

3 分析结果

马鞍山组两个石英砂岩样品 WFS-1 和 WFS11 的碎屑锆石 U-Pb 年龄分析结果见表 1，选择样品 WFS-1 做锆石 Hf 同位素分析，其结果见表 2。

表1　华北克拉通南缘嵩山地区五佛山群石英砂岩碎屑锆石U-Pb年龄数据

Table 1　U-Pb analytical data of detrital zircon from quartz sandstones of the Wufoshan Group in the south margin of the North China Craton.

分析点号	Th (μg/g)	U (μg/g)	Pb* (μg/g)	Th/U	同位素比值						同位素年龄 (Ma)					
					$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ
样品: WFS-1																
01	450	455	406	0.99	0.1332	0.0025	6.8127	0.1205	0.3710	0.0051	2140	14	2087	16	2034	24
02	445	453	404	0.98	0.0677	0.0027	0.5851	0.0223	0.0627	0.0008	860	85	468	14	392	5
03	25	70	13	0.35	0.1129	0.0014	1.5509	0.0173	0.0996	0.0011	1847	9	951	7	612	6
04	25	71	14	0.36	0.1224	0.0025	5.9938	0.1023	0.3552	0.0040	1991	37	1975	15	1959	19
05	13	240	23	0.05	0.1329	0.0029	7.0383	0.1294	0.3843	0.0046	2136	39	2116	16	2096	21
06	36	59	25	0.6	0.1180	0.0039	4.9892	0.1496	0.3067	0.0039	1926	60	1817	25	1724	19
07	229	1105	84	0.21	0.1271	0.0014	6.5953	0.0683	0.3764	0.0041	2058	9	2059	9	2059	19
08	1041	809	100	1.29	0.1270	0.0014	6.3609	0.0675	0.3631	0.0040	2057	9	2027	9	1997	19
09	172	265	109	0.65	0.1196	0.0015	3.7685	0.0437	0.2286	0.0025	1950	9	1586	9	1327	13
10	67	93	44	0.72	0.2012	0.0020	4.8924	0.0427	0.1764	0.0019	2836	8	1801	7	1047	10
11	273	187	84	1.46	0.1209	0.0024	3.2027	0.0508	0.1921	0.0021	1970	35	1458	12	1133	12
12	62	105	46	0.59	0.1268	0.0017	6.4931	0.0853	0.3715	0.0044	2054	10	2045	12	2036	21
13	38	104	42	0.37	0.1282	0.0014	6.7810	0.0714	0.3836	0.0042	2074	9	2083	9	2093	20
14	217	212	56	1.02	0.1174	0.0044	5.2224	0.1824	0.3227	0.0044	1917	69	1856	30	1803	21
15	1031	609	136	1.69	0.2578	0.0027	7.0440	0.0643	0.1982	0.0022	3233	8	2117	8	1165	12
16	27	76	14	0.35	0.0869	0.0021	0.7559	0.0164	0.0631	0.0007	1359	48	572	9	394	4
17	207	476	104	0.43	0.1183	0.0011	5.7217	0.0489	0.3509	0.0036	1930	8	1935	7	1939	17
18	53	104	45	0.51	0.1417	0.0016	6.5828	0.0688	0.337	0.0037	2248	9	2057	9	1872	18
19	87	144	65	0.60	0.1419	0.0014	7.2062	0.0655	0.3683	0.0039	2250	8	2137	8	2021	18
20	433	240	116	1.8	0.1467	0.0015	8.6743	0.0833	0.4287	0.0046	2308	8	2304	9	2300	21
21	513	588	148	0.87	0.1060	0.0015	1.6158	0.0213	0.1105	0.0012	1732	11	976	8	676	7
22	370	1081	83	0.34	0.1357	0.0016	7.2506	0.0802	0.3875	0.0043	2173	9	2143	10	2111	20
23	190	249	106	0.76	0.1082	0.0025	3.3303	0.0678	0.2233	0.0026	1769	44	1488	16	1299	14
24	191	210	78	0.91	0.1480	0.0012	8.5243	0.0642	0.4177	0.0042	2323	8	2289	7	2250	19
25	193	237	103	0.82	0.1228	0.0011	6.1609	0.0540	0.3637	0.0038	1998	8	1999	8	2000	18
26	103	129	69	0.80	0.1141	0.0013	3.7056	0.0388	0.2355	0.0025	1866	9	1573	8	1363	13
27	13	255	24	0.05	0.1716	0.0014	11.947	0.0905	0.505	0.0052	2573	8	2600	7	2635	22
28	26	75	14	0.35	0.1149	0.0010	5.3774	0.0429	0.3393	0.0034	1879	8	1881	7	1883	16
29	27	74	14	0.36	0.1247	0.0021	5.5744	0.0884	0.3242	0.0041	2025	13	1912	14	1810	20
30	454	459	406	0.99	0.1185	0.0011	5.0007	0.0428	0.306	0.0031	1934	8	1819	7	1721	15
31	528	597	80	0.88	0.1068	0.0021	1.3182	0.0211	0.0895	0.0010	1746	36	854	9	553	6
32	62	98	44	0.63	0.1155	0.0012	5.2960	0.0512	0.3325	0.0035	1888	8	1868	8	1850	17
33	127	281	78	0.45	0.1266	0.0010	6.5121	0.0499	0.3732	0.0037	2051	8	2048	7	2044	18
34	148	227	113	0.65	0.1184	0.002	5.4759	0.0882	0.3354	0.0043	1932	13	1897	14	1865	21
35	154	196	87	0.78	0.1236	0.0012	4.8029	0.0438	0.2819	0.0029	2008	8	1785	8	1601	15
36	210	348	96	0.60	0.1447	0.0011	7.2613	0.0542	0.3641	0.0037	2284	8	2144	7	2001	17
37	89	169	103	0.53	0.1125	0.0012	2.6109	0.0254	0.1684	0.0017	1840	8	1304	7	1003	10
38	145	293	113	0.5	0.1831	0.0022	6.6989	0.0735	0.2653	0.0031	2681	9	2072	10	1517	16
39	52	45	19	1.14	0.1457	0.0012	8.5223	0.0692	0.4243	0.0044	2296	8	2288	7	2280	20
40	121	319	107	0.38	0.1198	0.0015	5.2370	0.0603	0.317	0.0035	1954	9	1859	10	1775	17
41	26	72	14	0.36	0.1226	0.0014	5.8230	0.0615	0.3445	0.0037	1994	9	1950	9	1908	18
42	300	755	78	0.40	0.1612	0.0016	8.1170	0.0777	0.3653	0.0040	2468	8	2244	9	2007	19
43	264	211	92	1.25	0.1147	0.0011	3.8714	0.0361	0.2449	0.0025	1874	8	1608	8	1412	13
44	126	238	102	0.53	0.1121	0.0010	5.1869	0.0444	0.3357	0.0034	1833	8	1850	7	1866	17
45	29	51	20	0.58	0.1201	0.0014	5.8653	0.065	0.3542	0.0039	1958	9	1956	10	1955	19
46	219	334	108	0.65	0.1107	0.0028	2.7714	0.063	0.1816	0.0021	1810	48	1348	17	1076	12
47	142	299	125	0.47	0.1191	0.0012	4.8160	0.0449	0.2934	0.0031	1942	8	1788	8	1659	15

(续表1)

分析点号	Th (μg/g)	U (μg/g)	Pb* (μg/g)	Th/U	同位素比值						同位素年龄 (Ma)					
					$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ
48	197	483	88	0.41	0.1275	0.0012	6.7273	0.0616	0.3827	0.004	2064	8	2076	8	2089	19
49	229	171	57	1.33	0.1093	0.0010	4.9562	0.0418	0.329	0.0033	1787	8	1812	7	1833	16
50	118	169	87	0.69	0.1227	0.0020	6.0606	0.0928	0.3584	0.0045	1995	12	1985	13	1975	21
51	55	138	48	0.4	0.1242	0.0014	6.3651	0.0675	0.3716	0.0041	2018	9	2027	9	2037	19
52	13	253	24	0.05	0.1484	0.0024	9.6371	0.1509	0.4709	0.0064	2328	12	2401	14	2487	28
53	26	73	14	0.35	0.1157	0.0011	5.7184	0.052	0.3584	0.0037	1891	8	1934	8	1975	18
54	26	75	15	0.35	0.1209	0.0016	6.0163	0.0751	0.3608	0.0042	1970	10	1978	11	1986	20
55	459	461	416	1.0	0.1202	0.0011	5.7887	0.0494	0.3493	0.0036	1959	8	1945	7	1931	17
56	123	128	56	0.96	0.1186	0.0011	5.8378	0.049	0.3571	0.0037	1935	8	1952	7	1968	17
57	160	230	106	0.70	0.1827	0.0015	11.524	0.0874	0.4576	0.0047	2677	8	2567	7	2429	21
58	154	361	97	0.43	0.1244	0.0012	6.3163	0.0572	0.3682	0.0039	2021	8	2021	8	2021	18
59	289	228	102	1.27	0.183	0.0019	9.6692	0.0970	0.3832	0.0043	2681	8	2404	9	2091	20
60	128	121	57	1.06	0.1189	0.0012	5.7892	0.0538	0.3533	0.0037	1939	8	1945	8	1950	18
61	464	492	115	0.94	0.1613	0.0013	9.2558	0.0685	0.4161	0.0042	2470	8	2364	7	2243	19
62	223	285	97	0.78	0.1243	0.0014	6.1112	0.0650	0.3566	0.0039	2019	9	1992	9	1966	19
63	66	152	65	0.44	0.1386	0.0016	7.6262	0.0828	0.3992	0.0045	2209	9	2188	10	2165	21
64	168	267	101	0.63	0.1312	0.0016	5.4174	0.0602	0.2994	0.0033	2114	9	1888	10	1688	17
65	36	52	22	0.70	0.1179	0.0012	5.7046	0.0558	0.351	0.0037	1925	8	1932	8	1939	18
66	26	74	14	0.36	0.1362	0.0015	7.1543	0.0731	0.3811	0.0042	2179	9	2131	9	2082	19
67	28	113	45	0.25	0.1198	0.0012	5.4798	0.0527	0.3317	0.0035	1954	8	1897	8	1847	17
68	56	48	31	1.15	0.1344	0.0026	4.5164	0.0723	0.2437	0.0028	2156	35	1734	13	1406	14
69	159	191	84	0.83	0.1734	0.0031	9.7962	0.1361	0.4099	0.0047	2590	31	2416	13	2214	22
70	42	102	41	0.41	0.1187	0.0011	5.7479	0.0499	0.3512	0.0036	1937	8	1939	8	1940	17
71	85	197	77	0.43	0.1187	0.0010	4.6652	0.0387	0.2851	0.0029	1936	8	1761	7	1617	15
72	105	212	86	0.49	0.1235	0.0016	6.2793	0.0794	0.369	0.0043	2007	10	2016	11	2025	20
73	155	171	98	0.91	0.1253	0.0012	6.3687	0.0590	0.3688	0.0039	2033	8	2028	8	2024	18
74	124	162	71	0.76	0.1169	0.0013	5.7486	0.0595	0.3567	0.0039	1909	9	1939	9	1967	18
75	231	265	123	0.87	0.1109	0.0009	2.7614	0.0218	0.1807	0.0018	1813	8	1345	6	1071	10
76	127	172	73	0.74	0.1183	0.0013	5.7256	0.0612	0.351	0.0038	1931	9	1935	9	1939	18
77	12	276	26	0.04	0.1195	0.0011	5.7538	0.0479	0.3494	0.0036	1948	8	1939	7	1932	17
78	26	74	14	0.35	0.1179	0.0014	5.2908	0.0578	0.3256	0.0036	1924	9	1867	9	1817	17
79	27	76	14	0.36	0.1188	0.0015	5.7878	0.0707	0.3535	0.0040	1938	10	1945	11	1951	19
80	470	478	424	0.98	0.1358	0.0012	6.1723	0.0529	0.3298	0.0034	2174	8	2001	7	1837	17
样品: WFS11																
01	2572	17615	28	0.15	0.1289	0.0010	6.7226	0.0499	0.3781	0.0044	2084	13	2068	21	2076	7
02	1487	13072	23	0.11	0.1487	0.0010	8.7697	0.0589	0.4277	0.0049	2331	11	2295	22	2314	6
03	1395	26875	35	0.05	0.1184	0.0008	5.6743	0.0376	0.3476	0.0039	1932	12	1923	19	1928	6
04	1090	8022	11	0.14	0.1270	0.0012	6.0263	0.0546	0.3442	0.0042	2057	17	1907	20	1980	8
05	1062	3704	6	0.29	0.1278	0.0015	6.0183	0.0648	0.3415	0.0045	2068	20	1894	21	1979	9
06	1131	3692	6	0.31	0.1205	0.0015	5.7425	0.0677	0.3456	0.0046	1964	22	1913	22	1938	10
07	2379	13082	25	0.18	0.1461	0.0010	8.6501	0.0577	0.4295	0.0049	2300	11	2304	22	2302	6
08	3139	19242	29	0.16	0.1222	0.0008	6.0913	0.0412	0.3614	0.0041	1989	12	1989	20	1989	6
09	3139	9484	22	0.33	0.1637	0.0012	10.5455	0.0786	0.4671	0.0055	2495	12	2471	24	2484	7
10	3139	3116	5	1.01	0.1205	0.0017	5.8803	0.0772	0.3539	0.0050	1964	25	1953	24	1958	11
11	3139	10611	24	0.30	0.1583	0.0011	10.0292	0.0709	0.4594	0.0054	2438	12	2437	24	2438	7
12	3139	36285	34	0.09	0.1120	0.0015	3.6852	0.0443	0.2385	0.0032	1833	24	1379	17	1568	10
13	3139	5206	9	0.60	0.1328	0.0012	7.2550	0.0612	0.3963	0.0048	2135	15	2152	22	2143	8
14	3139	17095	24	0.18	0.1191	0.0008	5.8587	0.0402	0.3566	0.0041	1943	12	1966	19	1955	6

(续表1)

分析点号	Th (μg/g)	U (μg/g)	Pb* (μg/g)	Th/U	同位素比值						同位素年龄 (Ma)					
					$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ
15	3139	16720	26	0.19	0.1175	0.0009	5.7875	0.0430	0.3571	0.0042	1919	13	1968	20	1945	6
16	3139	3611	5	0.87	0.1248	0.0014	6.3313	0.0662	0.3678	0.0048	2027	19	2019	22	2023	9
17	3139	7973	11	0.39	0.1342	0.0016	6.8043	0.0752	0.3678	0.0049	2153	20	2019	23	2086	10
18	3139	15163	21	0.21	0.1237	0.0011	6.4160	0.0563	0.3763	0.0046	2010	16	2059	22	2035	8
19	3139	14407	22	0.22	0.1373	0.0009	7.0511	0.0487	0.3725	0.0043	2193	12	2041	20	2118	6
20	3139	5651	8	0.56	0.1098	0.0012	4.9055	0.0519	0.3241	0.0041	1796	20	1810	20	1803	9
21	3139	12794	21	0.25	0.1267	0.0009	6.6112	0.0465	0.3784	0.0044	2053	12	2069	20	2061	6
22	3139	5264	10	0.60	0.1639	0.0013	10.8864	0.0870	0.4817	0.0058	2496	13	2535	25	2514	7
23	3139	9316	13	0.34	0.1222	0.0016	5.5658	0.0659	0.3302	0.0045	1989	22	1840	22	1911	10
24	3139	3409	8	0.92	0.1582	0.0016	10.1140	0.0962	0.4637	0.0060	2437	17	2456	26	2445	9
25	3139	13530	20	0.23	0.1238	0.0009	6.3315	0.0446	0.3710	0.0043	2011	12	2034	20	2023	6
26	3139	19572	25	0.16	0.1080	0.0008	4.6131	0.0328	0.3098	0.0036	1766	13	1740	18	1752	6
27	3139	14033	26	0.22	0.1477	0.0010	9.1363	0.0645	0.4486	0.0052	2320	12	2389	23	2352	6
28	3139	13127	22	0.24	0.1268	0.0010	6.6514	0.0517	0.3806	0.0045	2054	14	2079	21	2066	7
29	3139	12184	18	0.26	0.1108	0.0008	4.9838	0.0365	0.3262	0.0038	1813	13	1820	18	1817	6
30	3139	19628	43	0.16	0.1627	0.0010	10.3946	0.0655	0.4634	0.0053	2484	10	2454	23	2471	6
31	3139	6220	11	0.50	0.1281	0.0012	6.6893	0.0584	0.3787	0.0046	2072	16	2070	22	2071	8
32	3139	9196	19	0.34	0.1592	0.0011	10.0528	0.0714	0.4580	0.0054	2447	12	2431	24	2440	7
33	3139	11609	21	0.27	0.1577	0.0010	9.4349	0.0597	0.4340	0.0049	2431	10	2324	22	2381	6
34	3139	10985	15	0.29	0.1061	0.0009	3.7915	0.0304	0.2591	0.0030	1734	15	1485	16	1591	6
35	3139	15821	23	0.20	0.1225	0.0009	6.0857	0.0424	0.3603	0.0041	1993	12	1983	20	1988	6
36	3139	10481	21	0.30	0.1653	0.0012	10.8684	0.0767	0.4770	0.0056	2510	12	2514	24	2512	7
37	3139	6702	9	0.47	0.1076	0.0010	4.5939	0.0415	0.3096	0.0038	1760	17	1739	18	1748	8
38	3139	6049	8	0.52	0.1102	0.0013	4.9125	0.0547	0.3234	0.0042	1802	21	1806	21	1804	9
39	3139	26102	45	0.12	0.1191	0.0008	5.8516	0.0387	0.3562	0.0041	1943	12	1964	19	1954	6
40	3139	9650	17	0.33	0.1364	0.0010	7.6474	0.0546	0.4067	0.0047	2182	12	2200	22	2190	6
41	3139	12132	20	0.26	0.1237	0.0009	6.3440	0.0468	0.3719	0.0043	2011	13	2038	20	2025	6
42	3139	13473	20	0.23	0.1170	0.0009	5.6380	0.0409	0.3494	0.0040	1912	13	1932	19	1922	6
43	3139	5201	5	0.60	0.1061	0.0016	3.4834	0.0470	0.2381	0.0033	1733	27	1377	17	1524	11
44	3139	9936	15	0.32	0.1183	0.0009	5.7615	0.0437	0.3533	0.0041	1931	14	1950	20	1941	7
45	3139	18849	30	0.17	0.1317	0.0008	7.2290	0.0474	0.3981	0.0045	2121	11	2160	21	2140	6
46	3139	5861	8	0.54	0.1141	0.0011	5.3096	0.0500	0.3375	0.0042	1866	18	1875	20	1870	8
47	3139	16312	23	0.19	0.1255	0.0010	6.4191	0.0521	0.3710	0.0044	2036	15	2034	21	2035	7
48	3139	3921	6	0.80	0.1080	0.0012	4.8589	0.0530	0.3263	0.0042	1766	21	1821	20	1795	9
49	3139	18514	43	0.17	0.1828	0.0013	12.9289	0.0931	0.5129	0.0061	2679	12	2669	26	2675	7
50	3139	7421	10	0.42	0.1099	0.0013	4.4496	0.0508	0.2937	0.0039	1797	22	1660	19	1722	9
51	3139	11778	12	0.27	0.1245	0.0012	6.3749	0.0587	0.3714	0.0046	2022	17	2036	22	2029	8
52	3139	24856	30	0.13	0.1193	0.0009	4.1581	0.0294	0.2528	0.0029	1946	13	1453	15	1666	6
53	3139	27447	22	0.11	0.1204	0.0013	4.6725	0.0486	0.2814	0.0036	1963	20	1599	18	1762	9
54	3139	8371	12	0.37	0.1263	0.0011	6.5188	0.0529	0.3744	0.0045	2047	15	2050	21	2048	7
55	3139	2150	3	1.46	0.1029	0.0018	4.6330	0.0769	0.3264	0.0049	1678	32	1821	24	1755	14
56	3139	28615	34	0.11	0.1389	0.0010	5.6667	0.0395	0.2959	0.0034	2213	12	1671	17	1926	6
57	3139	21526	34	0.15	0.1171	0.0008	5.7498	0.0412	0.3561	0.0041	1913	13	1963	20	1939	6
58	3139	7168	10	0.44	0.1175	0.0012	5.7381	0.0571	0.3542	0.0045	1919	19	1954	21	1937	9
59	3139	12922	29	0.24	0.1988	0.0015	14.8994	0.1114	0.5435	0.0065	2817	12	2798	27	2809	7
60	3139	3102	5	1.01	0.1050	0.0016	4.6787	0.0669	0.3233	0.0046	1714	28	1806	22	1763	12
61	3139	6496	8	0.48	0.1093	0.0015	4.3787	0.0546	0.2905	0.0040	1788	24	1644	20	1708	10
62	3139	3792	5	0.83	0.1117	0.0014	5.1309	0.0594	0.3333	0.0044	1827	22	1854	21	1841	10
63	3139	3813	6	0.82	0.1059	0.0019	4.8140	0.0799	0.3297	0.0050	1730	32	1837	24	1787	14

(续表1)

分析点号	Th (μg/g)	U (μg/g)	Pb* (μg/g)	Th/U	同位素比值						同位素年龄 (Ma)					
					$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ
64	3139	4670	8	0.67	0.1276	0.0012	6.5721	0.0597	0.3735	0.0046	2066	16	2046	22	2056	8
65	3139	26510	38	0.12	0.1285	0.0008	5.9108	0.0378	0.3337	0.0038	2078	11	1856	18	1963	6
66	3139	16450	28	0.19	0.1314	0.0009	7.0465	0.0499	0.3889	0.0045	2117	12	2118	21	2117	6
67	3139	3281	5	0.96	0.1115	0.0014	5.1505	0.0621	0.3352	0.0045	1823	23	1863	22	1845	10
68	3139	20591	28	0.15	0.1141	0.0009	4.8280	0.0366	0.3069	0.0036	1866	14	1725	18	1790	6
69	3139	17290	27	0.18	0.1328	0.0009	7.4343	0.0496	0.4061	0.0046	2135	11	2197	21	2165	6
70	3139	4433	7	0.71	0.1142	0.0012	5.5211	0.0567	0.3506	0.0045	1868	19	1937	21	1904	9
71	3139	15470	27	0.20	0.1444	0.0009	8.5395	0.0553	0.4290	0.0049	2280	11	2301	22	2290	6
72	3139	3366	5	0.93	0.1076	0.0014	4.9555	0.0608	0.3340	0.0045	1759	23	1858	22	1812	10
73	3139	9750	15	0.32	0.1171	0.0010	5.6351	0.0454	0.3490	0.0042	1913	15	1930	20	1922	7
74	3139	13760	23	0.23	0.1272	0.0016	6.7138	0.0776	0.3829	0.0052	2059	21	2090	24	2074	10
75	3139	11383	17	0.28	0.1239	0.0009	6.4696	0.0457	0.3789	0.0044	2012	12	2071	20	2042	6
76	3139	5046	7	0.62	0.1017	0.0012	3.9003	0.0439	0.2783	0.0036	1655	22	1583	18	1614	9
77	3139	11996	20	0.26	0.1451	0.0011	8.2190	0.0595	0.4109	0.0048	2289	12	2219	22	2255	7
78	3139	13383	26	0.23	0.1467	0.0010	8.7697	0.0579	0.4335	0.0050	2308	11	2322	22	2314	6
79	3139	20031	28	0.16	0.1263	0.0009	5.8300	0.0410	0.3348	0.0039	2047	12	1862	19	1951	6
80	3139	6782	12	0.46	0.1418	0.0011	8.2520	0.0633	0.4222	0.0050	2249	13	2270	23	2259	7
81	3139	12964	19	0.24	0.1177	0.0009	5.8923	0.0429	0.3632	0.0042	1921	13	1997	20	1960	6
82	3139	10694	17	0.29	0.1223	0.0009	6.2554	0.0464	0.3709	0.0043	1991	13	2034	20	2012	7
83	3139	8011	11	0.39	0.1082	0.0010	4.8051	0.0424	0.3221	0.0039	1769	17	1800	19	1786	7
84	3139	19024	26	0.17	0.1217	0.0008	6.0012	0.0398	0.3576	0.0041	1982	12	1971	19	1976	6
85	3139	15955	25	0.20	0.1167	0.0009	5.7570	0.0418	0.3579	0.0042	1906	13	1972	20	1940	6
86	3139	9924	14	0.32	0.1171	0.0010	5.9034	0.0475	0.3655	0.0043	1913	15	2008	21	1962	7
87	3139	19435	34	0.16	0.1188	0.0008	5.7102	0.0376	0.3486	0.0040	1938	12	1928	19	1933	6
88	3139	6468	9	0.49	0.1120	0.0011	5.0042	0.0478	0.3242	0.0040	1832	18	1810	20	1820	8
89	3139	11305	16	0.28	0.1088	0.0008	4.9320	0.0376	0.3288	0.0038	1779	14	1833	19	1808	6

表2 华北克拉通南缘嵩山地区五佛山群石英砂岩(WFS-1)碎屑锆石Hf同位素分析结果

Table 2 Hf isotopic data of detrital zircon from sample WFS-1 of the Wufoshan Group in the south margin of the North China Craton

分析点号	年龄 (Ma)	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf(m)$	2σ	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM1} (Ma)	$f_{Lu/Hf}$	t_{DM2} (Ma)
WFS-1 01	2140	0.010318	0.000364	0.281488	0.000020	–45.4	2.0	2425	–0.99	2603
WFS-1 02	860	0.083333	0.001968	0.281159	0.000029	–57.1	–39.3	2990	–0.94	4176
WFS-1 03	1847	0.148786	0.003595	0.281700	0.000022	–37.9	–1.2	2334	–0.89	2572
WFS-1 04	1991	0.023002	0.000736	0.281502	0.000020	–44.9	–1.4	2430	–0.98	2698
WFS-1 05	2136	0.008379	0.000264	0.281164	0.000013	–56.9	–9.5	2853	–0.99	3304
WFS-1 06	1926	0.067392	0.001946	0.281541	0.000019	–43.5	–3.1	2454	–0.94	2748
WFS-1 07	2058	0.021681	0.000700	0.281459	0.000015	–46.4	–1.4	2486	–0.98	2748
WFS-1 08	2057	0.034861	0.001145	0.281644	0.000014	–39.9	4.5	2261	–0.97	2382
WFS-1 09	1950	0.033131	0.000933	0.281541	0.000015	–43.5	–1.2	2389	–0.97	2653
WFS-1 10	2836	0.065236	0.001706	0.280788	0.000018	–70.2	–9.7	3479	–0.95	3844
WFS-1 11	1970	0.039308	0.001178	0.281525	0.000024	–44.1	–1.7	2426	–0.96	2695
WFS-1 12	2054	0.009175	0.000296	0.281615	0.000020	–40.9	4.6	2251	–0.99	2374
WFS-1 13	2074	0.023078	0.000719	0.281576	0.000019	–42.3	3.1	2328	–0.98	2483
WFS-1 14	1917	0.026397	0.000698	0.281572	0.000022	–42.4	–0.6	2333	–0.98	2587

(续表 2)

分析点号	年龄 (Ma)	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$(m)	2σ	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM1} (Ma)	$f_{Lu/Hf}$	t_{DM2} (Ma)
WFS-1 15	3233	0.073655	0.002123	0.280430	0.000028	–82.8	–14.5	4009	–0.94	4436
WFS-1 16	1359	0.120816	0.002982	0.281705	0.000026	–37.7	–10.3	2286	–0.91	2763
WFS-1 17	1930	0.026681	0.000844	0.281537	0.000014	–43.7	–1.7	2389	–0.97	2667
WFS-1 18	2248	0.033530	0.000953	0.281264	0.000021	–53.3	–4.5	2767	–0.97	3079
WFS-1 19	2250	0.021485	0.000666	0.281247	0.000020	–53.9	–4.6	2770	–0.98	3088
WFS-1 20	2308	0.019034	0.000608	0.281186	0.000017	–56.1	–5.4	2848	–0.98	3180
WFS-1 21	1732	0.048887	0.001414	0.281636	0.000020	–40.2	–3.2	2288	–0.96	2611
WFS-1 22	2173	0.016930	0.000528	0.281434	0.000018	–47.3	0.5	2509	–0.98	2717
WFS-1 23	1769	0.022171	0.000684	0.281278	0.000020	–52.8	–14.3	2730	–0.98	3318
WFS-1 24	2323	0.016392	0.000517	0.281177	0.000016	–56.4	–5.2	2853	–0.98	3181
WFS-1 25	1998	0.018126	0.000609	0.281454	0.000015	–46.6	–2.8	2487	–0.98	2788
WFS-1 26	1866	0.016873	0.000543	0.281594	0.000020	–41.7	–0.7	2293	–0.98	2557
WFS-1 27	2573	0.017030	0.000558	0.281038	0.000017	–61.3	–4.5	3043	–0.98	3332
WFS-1 28	1879	0.013222	0.000430	0.281414	0.000018	–48.0	–6.7	2530	–0.99	2935
WFS-1 29	2025	0.021815	0.000693	0.281347	0.000016	–50.4	–6.1	2637	–0.98	3012
WFS-1 30	1934	0.010044	0.000247	0.281548	0.000016	–43.3	–0.4	2338	–0.99	2592
WFS-1 31	1746	0.064755	0.001812	0.281421	0.000018	–47.8	–11.0	2612	–0.95	3100
WFS-1 32	1888	0.019596	0.000584	0.281226	0.000016	–54.7	–13.3	2792	–0.98	3350
WFS-1 33	2051	0.015134	0.000492	0.281535	0.000012	–43.8	1.4	2370	–0.99	2568
WFS-1 34	1932	0.011550	0.000373	0.281514	0.000014	–44.5	–1.9	2391	–0.99	2678
WFS-1 35	2008	0.028715	0.000905	0.281621	0.000018	–40.7	3.0	2277	–0.97	2440
WFS-1 36	2284	0.015407	0.000477	0.281198	0.000019	–55.7	–5.3	2822	–0.99	3157
WFS-1 37	1840	0.045517	0.001296	0.281518	0.000021	–44.3	–4.9	2443	–0.96	2797
WFS-1 38	2681	0.035561	0.001066	0.280739	0.000020	–71.9	–13.6	3486	–0.97	3966
WFS-1 39	2296	0.027936	0.000904	0.281289	0.000017	–52.4	–2.4	2730	–0.97	2991
WFS-1 40	1954	0.015224	0.000496	0.281581	0.000018	–42.1	0.9	2308	–0.99	2528
WFS-1 41	1994	0.041264	0.001284	0.281580	0.000015	–42.1	0.7	2357	–0.96	2570
WFS-1 42	2468	0.018810	0.000592	0.281353	0.000018	–50.2	4.2	2622	–0.98	2717
WFS-1 43	1874	0.018008	0.000514	0.281588	0.000016	–41.9	–0.7	2299	–0.98	2562
WFS-1 44	1833	0.038362	0.001443	0.281462	0.000016	–46.3	–7.3	2531	–0.96	2936
WFS-1 45	1958	0.026983	0.000860	0.281563	0.000019	–42.7	–0.2	2354	–0.97	2593
WFS-1 46	1810	0.079535	0.002259	0.281612	0.000022	–41.0	–3.4	2374	–0.93	2682
WFS-1 47	1942	0.039958	0.001253	0.281652	0.000022	–39.6	2.1	2256	–0.96	2440
WFS-1 48	2064	0.042022	0.001470	0.281534	0.000017	–43.8	0.3	2433	–0.96	2646
WFS-1 49	1787	0.015778	0.000512	0.281396	0.000017	–48.7	–9.5	2559	–0.98	3036
WFS-1 50	1995	0.014515	0.000480	0.281555	0.000019	–43.0	0.9	2343	–0.99	2558
WFS-1 51	2018	0.007720	0.000294	0.281574	0.000014	–42.4	2.3	2306	–0.99	2487
WFS-1 52	2328	0.018209	0.000615	0.281063	0.000018	–60.4	–9.3	3014	–0.98	3435
WFS-1 53	1891	0.009484	0.000334	0.281480	0.000013	–45.7	–3.9	2434	–0.99	2774
WFS-1 54	1970	0.007932	0.000285	0.281541	0.000014	–43.5	0.1	2350	–0.99	2589
WFS-1 55	1959	0.007549	0.000263	0.281563	0.000017	–42.8	0.6	2318	–0.99	2545
WFS-1 56	1935	0.005729	0.000186	0.281597	0.000014	–41.5	1.4	2268	–0.99	2478
WFS-1 57	2677	0.021363	0.000704	0.281218	0.000018	–54.9	4.0	2812	–0.98	2894
WFS-1 58	2021	0.016623	0.000540	0.281639	0.000015	–40.1	4.4	2232	–0.98	2363
WFS-1 59	2681	0.076117	0.001866	0.281149	0.000022	–57.4	–0.5	2994	–0.94	3170

(续表 2)

分析点号	年龄 (Ma)	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf(m)$	2σ	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM1} (Ma)	$f_{Lu/Hf}$	t_{DM2} (Ma)
WFS-1 60	1939	0.014069	0.000491	0.281526	0.000016	–44.1	–1.4	2382	–0.99	2657
WFS-1 61	2470	0.022890	0.000728	0.281091	0.000016	–59.4	–5.3	2984	–0.98	3298
WFS-1 62	2019	0.023619	0.000777	0.281239	0.000018	–54.2	–10.2	2789	–0.98	3257
WFS-1 63	2209	0.014713	0.000503	0.281272	0.000018	–53.1	–4.4	2726	–0.98	3046
WFS-1 64	2114	0.016928	0.000546	0.281457	0.000016	–46.5	0.0	2479	–0.98	2705
WFS-1 65	1925	0.012233	0.000402	0.281512	0.000014	–44.6	–2.1	2395	–0.99	2689
WFS-1 66	2179	0.027967	0.000912	0.281229	0.000018	–54.6	–7.2	2813	–0.97	3195
WFS-1 67	1954	0.052140	0.001783	0.281491	0.000023	–45.3	–4.0	2513	–0.95	2829
WFS-1 68	2156	0.031904	0.000990	0.281124	0.000020	–58.3	–11.6	2961	–0.97	3442
WFS-1 69	2590	0.007533	0.000291	0.280863	0.000017	–67.5	–9.9	3254	–0.99	3672
WFS-1 70	1937	0.001183	0.000040	0.281321	0.000016	–51.3	–8.2	2628	–1.00	3069
WFS-1 71	1936	0.031189	0.001108	0.281610	0.000023	–41.1	0.7	2306	–0.97	2525
WFS-1 72	2007	0.017920	0.000603	0.281600	0.000016	–41.4	2.6	2288	–0.98	2461
WFS-1 73	2033	0.011191	0.000413	0.281567	0.000017	–42.6	2.2	2323	–0.99	2503
WFS-1 74	1909	0.009723	0.000316	0.281526	0.000019	–44.1	–1.9	2372	–0.99	2662
WFS-1 75	1813	0.099965	0.002686	0.281538	0.000025	–43.7	–6.5	2508	–0.92	2874
WFS-1 76	1931	0.029150	0.000959	0.281568	0.000016	–42.6	–0.7	2354	–0.97	2608
WFS-1 77	1948	0.030228	0.001071	0.281567	0.000017	–42.6	–0.5	2362	–0.97	2609
WFS-1 78	1924	0.018727	0.000639	0.281526	0.000022	–44.1	–1.9	2391	–0.98	2677
WFS-1 79	1938	0.012053	0.000421	0.281563	0.000018	–42.8	0.0	2328	–0.99	2571
WFS-1 80	2174	0.020106	0.000681	0.281274	0.000019	–53.0	–5.4	2735	–0.98	3078

马鞍山组底部石英砂岩 WFS11 的碎屑锆石大小不均匀, 粒径最小为 25 μm, 最大达到 230 μm, 大多数介于 80~180 μm 之间, 形状为次圆状和次棱角状。阴极发光(CL)图像显示(图 2), 大多数锆石无分带或弱分带, 部分锆石呈长柱状, 可见岩浆震荡环带, 少数锆石具有面状分带、扇形分带和溶蚀结构。对该石英砂岩样品共进行了 89 个碎屑锆石分析。最年轻的碎屑锆石 $^{207}Pb/^{206}Pb$ 年龄为(1655±22) Ma。除三个较老的太古宙的锆石年龄外, 其余的碎屑锆石在 $^{207}Pb/^{206}Pb$ 年龄频率分布直方图上有四组比较明显的分布区间(图 3), 分别为: (1) 2.50~2.38 Ga; (2) 2.34~2.24 Ga; (3) 2.24~1.90 Ga; (4) 1.90~1.65 Ga。该样品共有 62 个锆石年龄分布于 2.10~1.70 Ga 之间, 占统计总数的 70%, 形成一个最高的年龄峰, 峰值为 1.92 Ga, 次年龄峰值为 20.50 Ga。

马鞍山组细粒岩屑石英砂岩样品 WFS-1 的碎屑锆石大小不等, 粒径最小可至 10 μm, 最大至 350 μm, 大部分在 200~250 μm 之间。其 CL 图像显示, 大部分锆石呈次圆状和柱状, 但也有少量晶型较好的碎屑锆石存在。部分具有岩浆震荡环带, 有的具有继承锆石核, 表明部分碎屑物质源区较近。还有部分变质锆石存在, 一些锆石颗粒的边部常出现一个很窄的(几微米)、不规则的变质增生边。笔者对样品 WFS-1 共进行了 80 个碎屑锆石分析, 剔除谐和度较差的 5 个点(WFS-1-2、10、15、16、38), 对剩下的 75 个点进行年龄统计。该样品的锆石 $^{207}Pb/^{206}Pb$ 年龄分布于 2681~1732 Ma 之间, 最年轻的年龄为(1732±11) Ma。其中有 4 个较老的太古宙的锆石年龄, 50 个分析点的锆石年龄在 2.10~1.80 Ga 之间, 占统计总数的 67%。锆石 $^{207}Pb/^{206}Pb$ 年龄频率分布直方图显示(图 3), 锆石年龄形成一个明显的主峰, 其峰值约为 1.94 Ga。

石英砂岩样品 WFS-1 的碎屑锆石 Hf 同位素分析结果显示(图 4), 大部分锆石的 $^{176}Lu/^{177}Hf$ 比值均小于 0.002, $^{176}Hf/^{177}Hf$ 比值为 0.280863~0.281700, $\varepsilon_{Hf}(t)$ 值变化较大, 介于–14.3~4.6 之间, 平均为 –2.51。大多数 1.90 Ga 左右的碎屑锆石的 $\varepsilon_{Hf}(t)$ 值相对比较集中, 介于–5~4.6 之间(图 4)。所有锆石的两阶段模式年龄分布于 2363~3672 Ma 之间, 明显大于其 $^{207}Pb/^{206}Pb$ 年龄, 大部分锆石的 Hf 同位素组成位于 2.50 Ga 和 2.80 Ga 地壳演化线区域内(图 4)。

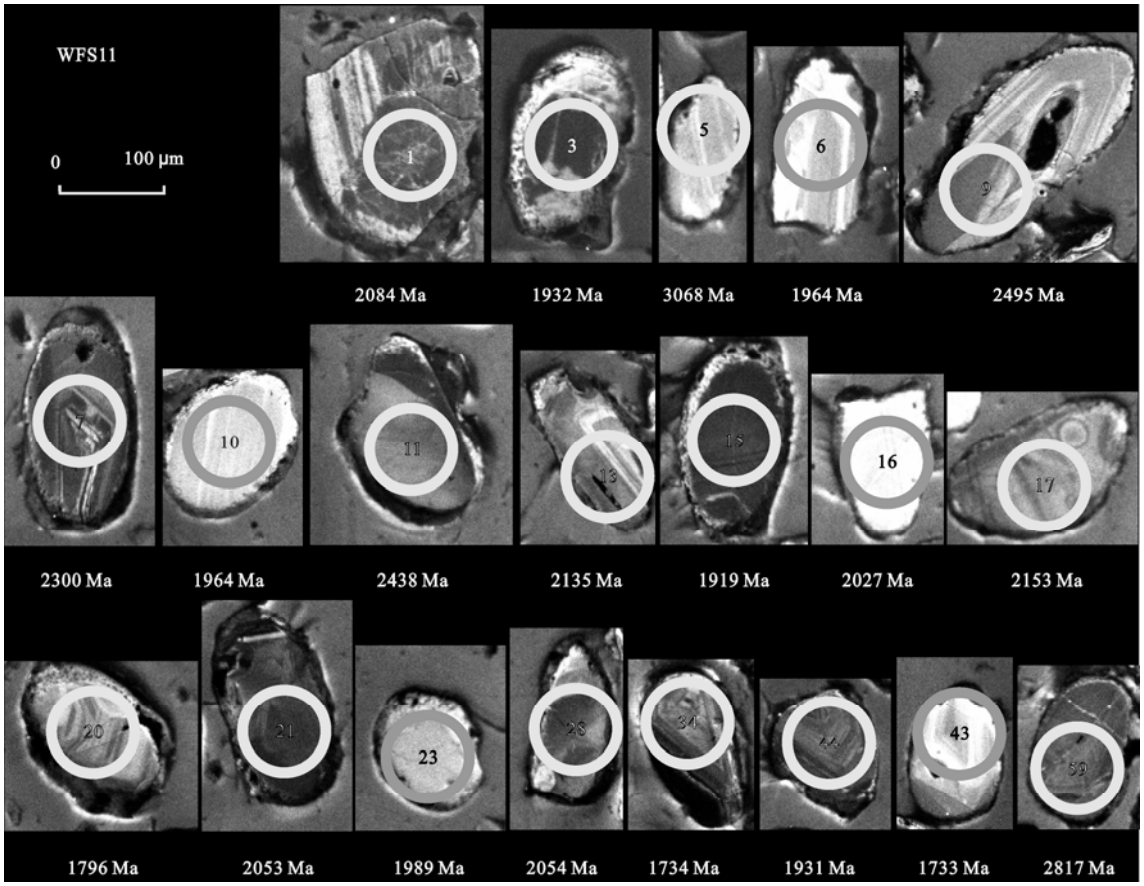

图2　五佛山群石英砂岩(WFS11)碎屑锆石CL图像

Fig.2　Representative CL images for detrital zircon from sample WFS11 of the Wufoshan Group

圆圈内数字为分析点号，碎屑锆石下方的年龄为其$^{207}Pb/^{206}Pb$年龄。

The numbers in circles are analytical plots and data under each photo are $^{207}Pb/^{206}Pb$ ages.

4　讨　论

4.1　五佛山群的形成时代

已有观点认为嵩山地区五佛山群底部马鞍山组的时代为蓟县纪(1400~1000 Ma)，葡峪组、骆驼畔组和何家寨组的时代为青白口纪(1000~800 Ma)[27,32]。因此，五佛山群地层大体可限定在蓟县纪-青白口纪地层范围内[18]。另据地质关系也可限定五佛山群至少在古元古代晚期之后沉积，并且沉积作用可延至新元古代早期。但一直缺少精确的年代学数据。

关保德等[18]发现五佛山群底部马鞍山组所含微古植物组合特征与华北克拉通南缘相邻地区(中条山、太行山地区)的汝阳群云梦山组极为相似，而葡峪组、骆驼畔组和何家寨组岩性和中条山、王屋山地区的洛峪群崔庄组、三教堂组的岩性也极为相似。因此，五佛山群的形成时代可以和汝阳群、洛峪群进行对比。汝阳群不整合于熊耳群(1.80~1.75 Ga)[21,37]之上，但在汝阳群云梦山组底部发现一层与熊耳群玄武安山岩岩性和地球化学特征相似的火山岩夹层，说明汝阳群继熊耳群之后不久开始沉积。洛峪群平行不整合覆盖于汝阳群之上，关保德等[18]获得洛峪群崔庄组下部年龄为1171 Ma和1150 Ma(海绿石Rb-Sr年龄)，崔庄组上部年龄为1013 Ma(海绿石K-Ar年龄)。因此，汝阳群应该形成于中元古代。

本文通过对五佛山群碎屑锆石U-Pb年龄分析，发现其底部马鞍山组两个石英砂岩样品最年轻的$^{207}Pb/^{206}Pb$年龄分别为(1732±11) Ma和(1655±22) Ma，该数据谐和性较好，从而限制了五佛山群的最大沉积年龄不早于1650 Ma。结合野外地质考察结果，笔者认为嵩山地区五佛山群的形成时代相当于长城纪(1800~1600 Ma)[38–40]晚期，可能与汝阳群沉积起始时间相近或稍晚。由于没有对五佛山群上部地层做年龄测试，笔者根据前人研究成果和野外地层关系，推断五佛山群自古元古代晚期(约1655 Ma)之后开

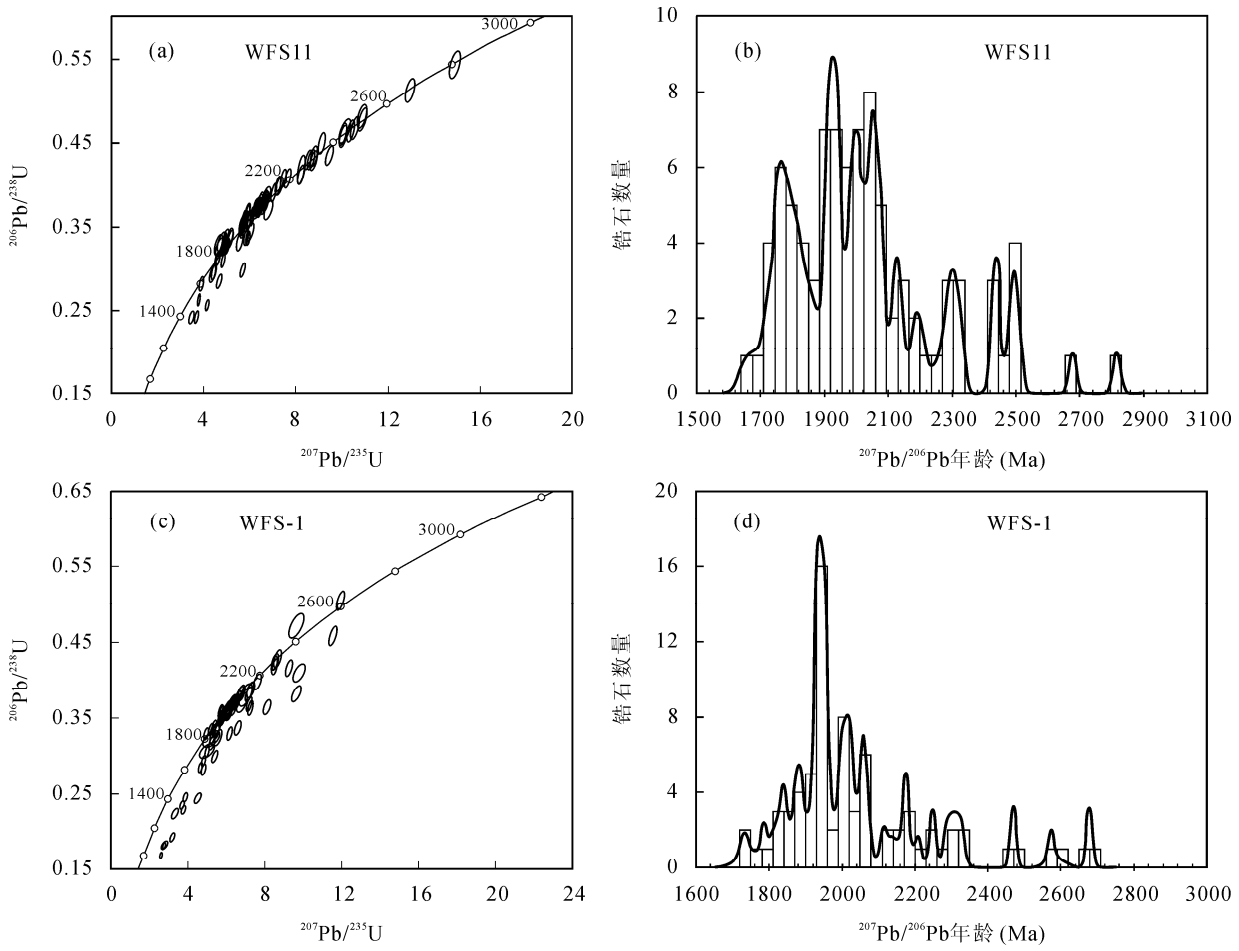

图3 五佛山群石英砂岩碎屑锆石U-Pb谐和图(a和c)和锆石年龄频率分布直方图(b和d)

Fig.3 U-Pb concordia diagrams (a and c) and age histograms (b and d) of detrital zircon from quartz sandstone of the Wufoshan Group

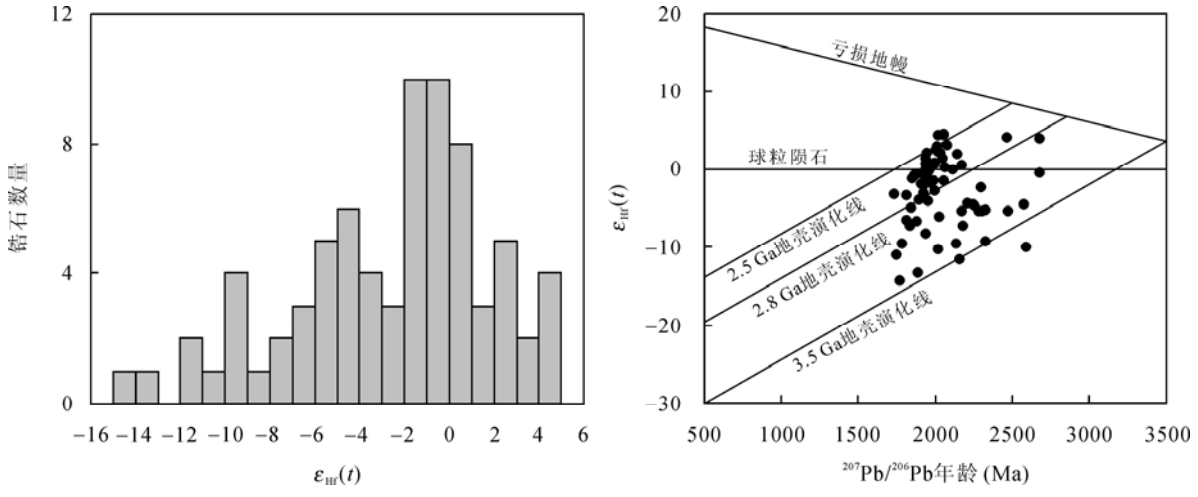

图4 五佛山群石英砂岩(WFS-1)碎屑锆石Hf同位素特征

Fig.4 Hf isotopic characteristics of detrital zircon from quartz sandstone of the Wufoshan Group

始沉积，可能延续到新元古代，目前只能将汝阳群与五佛山群下部地层进行对比，而洛峪群形成于新元古代，可以和五佛山群上部地层进行对比，它们都是在熊耳群火山-沉积作用之后形成的，表明华北克拉通南缘在古元古代晚期开始进入了一个稳定沉积的阶段。

4.2　物源区分析

通过对嵩山地区五佛山群马鞍山组两个石英砂岩进行碎屑锆石U-Pb年代学和Hf同位素分析, 得出以下几点认识。

(1) 在WFS-1和WFS11两个样品中存在少量较为古老的新太古代的锆石年龄, 所占比例较小, 分别为5.3%和3.4%。已有资料表明, 华北克拉通存在大于约3.00 Ga的古陆核[41−44], 在2.70 Ga和2.90 Ga发生过大规模的陆壳增生事件[42], 但是由于被后期地质事件改造而未留下大量的锆石记录。目前, 在嵩山地区发现较多的2.65~2.50 Ga的地质体[23−25], 河南鲁山[45−46]和山东西部[47]也发现有2.80~2.70 Ga的地质体, 主要为TTG片麻岩和少量表壳岩[42,48], 还有少量2.50 Ga左右的富钾花岗岩[30]。五佛山群2.85~2.50 Ga的碎屑锆石年龄可能是对这些古老地质事件的反映。太古宙岩浆事件在嵩山群碎屑锆石中记录很显著[23, 26]。虽然约2.50 Ga是华北克拉通重要的陆壳增生和克拉通化时期, 该时期的年龄记录在华北克拉通广泛存在[23,43,44,49], 但五佛山群约2.50 Ga的碎屑锆石所占比例较小(图3), 说明五佛山群的物源区并非主要来自太古宙的岩石。

(2) 从WFS-1和WFS11两个样品的年龄分布特征来看, 2.10~1.80 Ga的锆石年龄分布最为集中, 所占比例最多(分别为67%和55%), 指示五佛山群的源区物质主要以2.10~1.80 Ga的地质体为主, 与华北克拉通早前寒武纪重要的构造-热事件发生的时代相对应[42,50,51]。然而, 目前在嵩山地区发现的该时期的地质体很少, 但是在华北南缘周边地区发现大量2.10~1.80 Ga的地质体, 如太华群变质的中-基性火山岩、鲁山和中条山地区的花岗岩等, 它们可以为五佛山群的沉积提供物源。WFS-1的锆石年龄呈现出1.94 Ga的年龄峰值, WFS11的锆石年龄呈现出1.92 Ga的主峰值和2.05 Ga的次年龄峰值, 反映该时期内可能发生了一系列的构造-热事件。从锆石的CL图像特征上看, 大多数1.92 Ga和2.05 Ga左右的锆石具有变质锆石的特征, 少数具有岩浆锆石震荡环带结构, 表明提供这些锆石的物源区发生了一定程度的变质作用, 同时也伴随有岩浆活动。在华北克拉通其他地区也发现有该时期的变质作用, Santosh *et al*.[52]对内蒙古凉城集宁杂岩体中的麻粒岩进行了SHRIMP U-Pb定年, 得到了(1919±10) Ma的变质年龄, Yin *et al*.[53]在内蒙古千里山片麻岩中发现了大量的1.92~1.95 Ga的变质年龄, 时毓等[54]的研究结果显示小秦岭地区的太华群在约1.91 Ga经历了一期重要的变质热事件。翟明国[55]总结了华北克拉通元古宙麻粒岩的变质期次和年代, 指出峰期变质作用和退变麻粒岩相-高级角闪岩相的时代分别为约1.91 Ga和1.84 Ga, 本文获得的(1.93±0.10) Ga的碎屑锆石年龄峰值与约1.91 Ga的峰期变质作用的时代基本一致。

(3) 在WFS-1和WFS11的碎屑锆石中, 还有若干2.50~2.10 Ga和1.80~1.60 Ga的锆石年龄, 两个样品2.50~2.10 Ga的碎屑锆石所占比例分别为22.7%和24.7%, 1.80~1.60 Ga的碎屑锆石所占比例分别为5.3%和17.6%。嵩山地区广泛分布的古元古代嵩山群石英岩(2.00~2.45 Ga)[23,26]和路家沟钾长花岗岩((2424±24) Ma)[30]以及基性岩墙[56]等地质体可以为五佛山群提供沉积物质。WFS11显示有1.75 Ga的年龄峰值, 对应着华北克拉通1.80~1.60 Ga裂解事件发生的时间。华北克拉通南缘典型的岩浆活动是镁铁质岩墙群的侵入和熊耳群火山-沉积建造以及后造山花岗岩的侵位等[21,31,56−60], 它们均为五佛山群的沉积提供物源。

4.3　对华北克拉通南缘早前寒武纪地壳演化的制约

华北克拉通大规模陆壳物质的生长发生在新太古代(2.80~2.50 Ga), 同位素资料显示地壳物质生长的峰期在2.80~2.70 Ga[49], 与全球典型克拉通相似, 五佛山群石英砂岩(WFS-1)的Hf同位素组成大部分集中于2.50 Ga和2.80 Ga地壳演化线区域内(图4), 表明了这一时期为地壳的生长期。华北克拉通最强烈的岩浆活动出现在太古宙末2.55~2.50 Ga[61−62], 以TTG质片麻岩和登封群表壳岩为主, 这一岩浆活动主要在古元古界嵩山群记录比较丰富, 五佛山群仅有少量记录。嵩山群记录了大量新太古代(约2.50 Ga和2.75~2.80 Ga)的锆石年龄, 以约2.50 Ga的年龄峰值最为显著, 母岩岩浆以新太古代地壳再造为主并伴有少量古老地壳物质的再循环[26], 表明新太古代华北克拉通发生了大规模的岩浆活动。五佛山群两个石英砂岩样品碎屑锆石$^{207}Pb/^{206}Pb$年龄主要集中于2.10~1.80 Ga之间, 其峰值为(1.93±0.10) Ga, 还有部分2.50~2.10 Ga和少量新太古代以及古元古代晚期的年龄纪录。因此, 嵩山群和五佛山群分别记录了华北克拉通新太古代和古元古代重要的构造-热事件, 五佛山群碎屑锆石的年龄峰值(约1.93 Ga)

的发现表明华北克拉通南缘在最终克拉通化之前发生了一期重要的构造-热事件。

华北克拉通古元古代地质演化可以分为活动(造山)带的形成和基底隆升-裂谷事件, 分别与古元古代的哥伦比亚超大陆形成与裂解相对应[41,62–65]。翟明国[41,66]以及翟明国等[67]认为在2300~1950 Ma期间, 华北克拉通经历了一次基底陆块的拉伸-破裂事件, 形成晋豫、胶辽裂陷盆地和丰镇陆内凹陷盆地。在1950~1800 Ma期间, 华北克拉通经历了一次挤压构造事件, 导致裂陷盆地的闭合和焊接, 形成晋豫、胶辽及丰镇等类似于现代陆-陆碰撞型造山带, 大致相当于Zhao *et al.*[68]的中央造山带, 这一构造事件为五佛山群提供了主要的沉积物源。很多学者[68–70]提出2100~1800 Ma间有一个全球规模的造山活动, 并推测世界克拉通的拼合导致一个古元古代-中元古代的超级大陆(哥伦比亚超大陆)形成。该时期华北克拉通不同陆块相互碰撞拼合, 最终克拉通化, 为全球哥伦比亚超大陆形成作用的一部分。

5 结 论

(1) 五佛山群底部两个石英砂岩样品最年轻的碎屑锆石$^{207}Pb/^{206}Pb$年龄分别为(1732±11) Ma和(1655±22) Ma, 说明五佛山群沉积时代不早于1655 Ma。

(2) 五佛山群马鞍山组的碎屑锆石$^{207}Pb/^{206}Pb$年龄主要集中于2.10~1.80 Ga之间, 最大的峰值年龄为(1.93±0.10) Ga, 记录了华北克拉通南缘早前寒武纪重要的构造-热事件。

(3) 五佛山群马鞍山组的碎屑锆石$^{207}Pb/^{206}Pb$年龄分布特征表明, 古元古代的地质体为五佛山群的沉积提供了主要的物源, 其中2.10~1.80 Ga期间的物源较多, 而太古宙的物源很少。

(4) 五佛山群碎屑锆石 $\varepsilon_{Hf}(t)$值为–14.3~4.6, Hf的两阶段模式年龄分布于2363~3672 Ma之间, 大部分锆石的Hf同位素组成集中于2.50 Ga和2.80 Ga地壳演化线区域内, 说明新太古代为华北克拉通南缘重要的陆壳生长期。

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