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湘南—桂东北地区寒武—奥陶纪沉积岩碎屑锆石U-Pb年代学特征及其地质意义

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提要:本文利用LA-ICP-MS分析技术,对湘南—桂东北地区寒武纪和奥陶纪沉积岩进行了碎屑锆石U-Pb年代学研究。获得有效年龄数据239组,年龄值变化范围较大(3146~474 Ma),主要集中分布于2633~2473 Ma(峰值2500 Ma),1880~1521 Ma(峰值1650 Ma),1146~911 Ma(峰值970 Ma),896~720 Ma(峰值800 Ma)和682~474 Ma(峰值520 Ma)5个时间段。4件样品均记录了古太古代—中太古代年龄信息,同时以1146~911 Ma和896~720 Ma两个时间段年龄最集中,反映全球Grenville造山事件和全球Rodinia超大陆裂解事件对研究区影响显著。此外,本次还获得大量泛非期(520 Ma左右)锆石年龄,认为全球泛非事件对华夏地块及其邻区影响显著,反映华夏地块与冈瓦纳大陆可能有一定亲缘性。结合前人资料,认为研究区位于华夏地块和扬子地块西南段碰撞拼合带,研究区地层同时接受两地块物质沉积,物源主要来自华夏地块。

关 键 词:碎屑锆石U-Th-Pb同位素;华夏地块;扬子地块;湘南—桂东北
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Detrital zircon geochronology of Cambrian—Ordovician sedimentary rocks in southern Hunan—Northeast Guangxi area and its tectonic implications

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Abstract: In this paper, the authors studied detrital zircon geochronology of the Cambrian-Ordovician sedimentary rocks sampled

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from the southern Hunan to northeastern Guangxi area by using LA−ICP−MS and obtained 239 groups of effective age data, with the ages ranging from 3146 Ma to 474 Ma. Most of the data are concentrated in five periods, i.e., 2633−2473Ma (peak value around 2500 Ma), 1880−1521 Ma (peak value around 1650 Ma), 1146−911Ma (peak value around 970 Ma), 896−720 Ma (peak value around 800 Ma) and 682−474 Ma (peak value around 520 Ma). All the four samples recorded Paleoarchean − Mesoarchean information, and their ages are concentrated on 1146−911 Ma and 896−848 Ma, suggesting that the Grenville and Rodinia orogeny events profoundly influenced the study area. Moreover, the authors obtained a large number of ages representing the Pan−African time, implying that the global Pan−African event significantly affected the Cathaysia Block and its adjacent regions. Combined with previous researches, the authors hold that the study area is located in the southeast of the southwestern section of the collision orogenic belt between the Yangtze block and the Cathaysia block. The strata in the study area received material sources from the two blocks with the material from the Cathaysia block being dominant.

Key words: U−Th−Pb isotopic compositions of detrital zircons; Yangtze block; Cathaysia block; southern Hunan−northeast Guangxi

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华南板块由扬子地块和华夏地块拼贴而成，北西为扬子地块，南东为华夏地块，新元古代之前两地块并非统一大陆，具有不同的前寒武纪地壳演化历史[1-12]。华南板块以中生代秦岭—大别—苏鲁造山带为北界与华北板块分隔，北西以中生代−新生代的龙门山断裂为界与松潘甘孜地块相邻，南西以新生代的哀牢山—红河断裂为界与印支板块相邻，南东以新生代的东海和南海大陆斜坡为界。大量研究表明华南板块特别是华夏地块前寒武纪地壳演化与Columbia超大陆、Rodinia超大陆、Gondwana大陆等超大陆的循环密切相关[6, 11, 13-15]。虽然华南板块在各超大陆上的位置存在争议，但都位于碰撞或裂解的重要部位，对华南前寒武纪地质演化历史的研究显得尤为重要。

华夏地块前寒武纪演化历史以及华夏地块和扬子地块的碰撞聚合时间和界线位置，一直是华南基础地质关键科学问题。目前大部分学者认为扬子地块和华夏地块于中—新元古代（1.0 Ga左右）开始汇聚拼合，加里东运动后形成统一板块，其东段碰撞聚合界线为江绍断裂带[16-24]。但是，由于没有发现典型蛇绿岩套和构造混杂带等直接证据，加上显生宙以来多期的造山运动和岩浆活动，使得大量前寒武地质记录发生强烈的叠加和改造，区域构造变形十分复杂，扬子地块和华夏地块西南段碰撞聚合界线仍存在许多不同观点。如，钦州—岑溪—罗定—云浮构造混杂岩带[25]；茶陵—郴州断裂[26]；滇东南—黔西南的弥勒−师宗—罗平—兴义—望谟—罗甸一线[27, 28]；萍乡—衡阳东—北海一线[29]；钦杭结合带[30]；郴州—临武断裂[31, 32]；荔浦断裂[33]；苗儿山与金鸡岭之间[34, 35]等。

本次研究区位于湘南—桂东北地区，该区出露地层以古生代地层为主，零星分布少量元古宙地层，区内出露不同时代岩浆岩岩体，其中以古生代—中生代中酸性岩体为主，如花山、姑婆山、连山、九嶷山、海洋山、都庞岭等。由于出露古老变质基底较少，区域构造变形强烈，且未发现确凿证据的蛇绿岩，故相对于华南东部研究程度较低。研究区位于扬子地块和华夏地块碰撞结合带附近，北西侧为扬子地块西南缘，南东侧为华夏地块西北缘，是研究扬子地块与华夏地块碰撞聚合带的有利场所。本文试图通过对研究区寒武纪和奥陶纪沉积岩中碎屑锆石U−Th−Pb同位素研究，结合前人资料，对比华夏地块和扬子地块前寒武纪锆石年龄分布特征，判断研究区基底组成与扬子地块和华夏地块的亲缘性差异，进而为限定扬子地块和华夏地块西南段边界位置以及为二者之间的构造演化提供依据。

1 地质概况及样品描述

研究区位于湘南—桂东北地区，区域上位于南

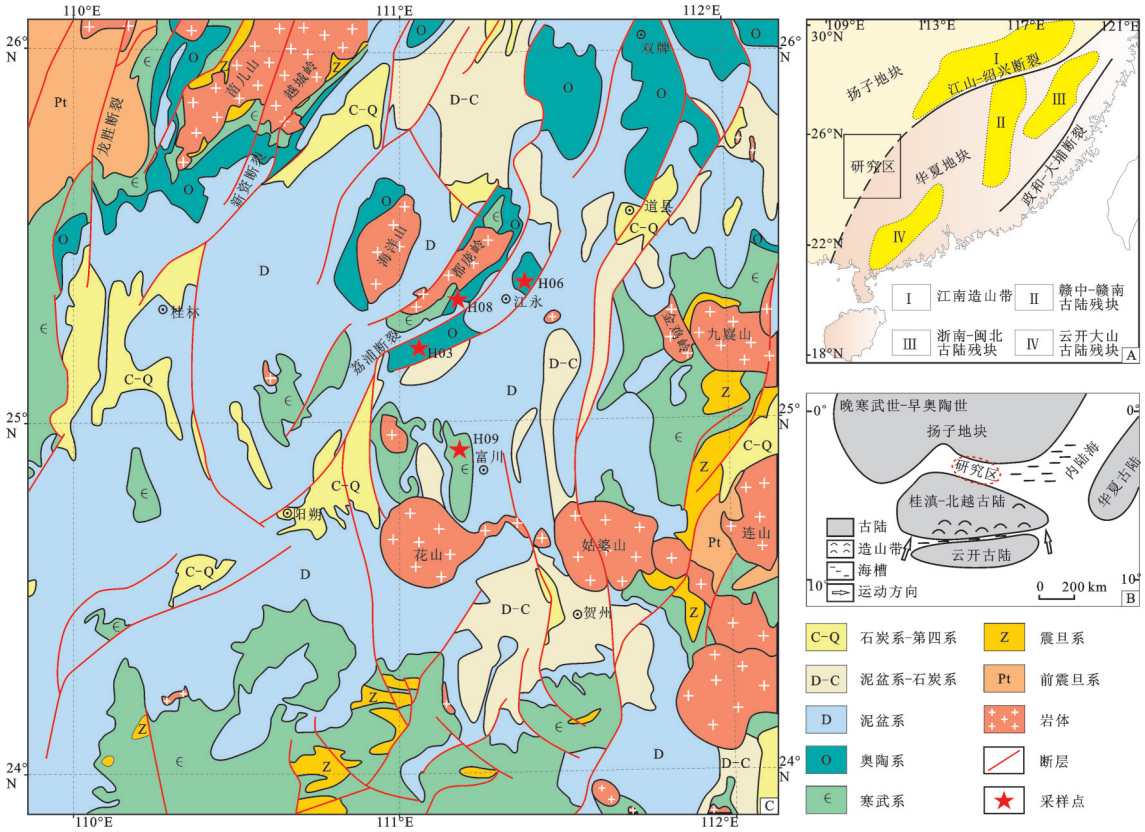

图1 A−华南古陆残块分布图(据文献[9]改编);B−湘南−桂东北及邻区晚寒武世−早奥陶世古地理示意图(据文献[38]改编);C−研究区区域地质简图及采样位置图(据1:250万地质图改编)

Fig.1 A−Sketch map showing distribution of continental blocks in South China (modified after [9]);B−Palaeogeographic map of southern Hunan −northeastern Guangxi and adjacent areas in the Late Cambrian to Early Ordovician (modified after [38]);C−Sketch geological map of the study area and sampling location (modified after 25 00000 geological map)

华裂谷盆地内桂东凹陷带,是扬子地块和华夏地块西南段边界交接地带。研究区地层以古生代地层为主,零星分布中元古代和中生代到第四纪地层。区内出露岩体较多,其中湘东南地区以燕山期花岗岩为主,桂东北地区以加里东期花岗岩为主,如海洋山、都庞岭等加里东期花岗闪长岩;九嶷山燕山期花岗闪长岩;花山—婆姑山、金鸡顶等燕山期花岗岩;以及岩鹰嘴等加里东期小型斑岩岩体[26, 36-38]。研究区断裂构造发育,为多期构造运动结果,控制着区内的沉积活动和岩浆活动,主要断裂有NE向的新资断裂带,龙胜断裂和荔浦断裂等。

本文4件样品均采自湖南江永—广西富川地区寒武纪和奥陶纪地层,奥陶纪地层包括黄隘组(O_1h)、桥亭子组($O_{1-2}q$)和天马山组(O_3t),主要为大陆边缘,前陆海盆相碎屑岩,发育水平层理、波状层理、透镜状层理、小型交错层理、火焰状构造、底模构造等沉积构造;寒武纪地层($\in b$)主要为浅海相碎屑岩,发育正粒序层理、水平层理、小型单向斜层理等。样品H06采自桃川镇北部天马山组(O_3t)地层,为绢云母凝灰质细砂岩,碎屑成分主要为零散均匀分布的棱角状碎屑石英和岩屑(图2−a);样品H03采自桃川镇鸡笼山西北侧桥亭子组($O_{1-2}q$)地层,为伊利石−绢云母凝灰质细砂岩,碎屑成分主要为零散分布的次棱角状石英细砂及粉砂(图2−b);样品H08采自源口瑶族乡西南侧黄隘组(O_1h)地层,为凝灰质细−粉砂岩,碎屑成分主要为零散均匀分布的棱角状−次棱角状碎屑石英(图2−c);样品H09采自鸟源山附近边溪组($\in b$)地层,为凝灰质细砂岩,碎屑成分为零散均匀分布的次棱角状碎屑石英(图2−d),4件样品磨圆度和分选性均较差,反映物质搬运

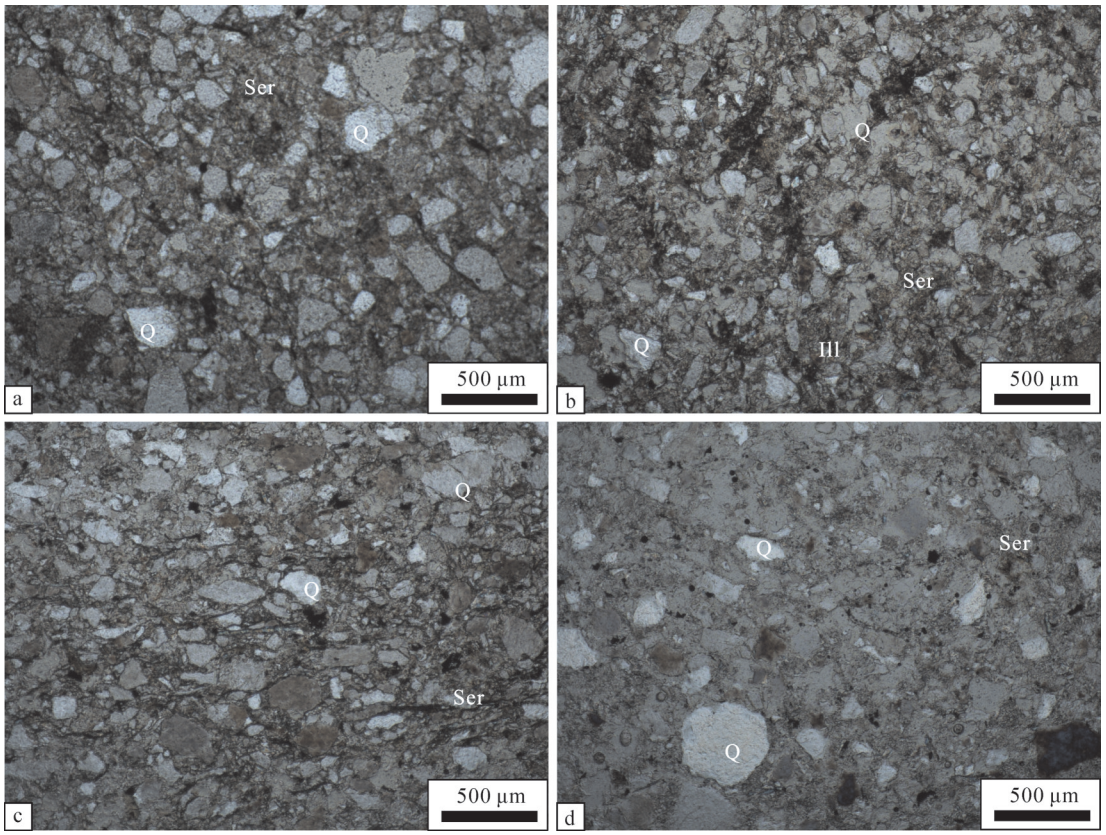

图2 湘南-桂东北地区寒武纪及奥陶纪沉积岩显微照片(5倍正交镜下照相)

a—奥陶纪天马山组绢云母凝灰质细砂岩(H06);b—奥陶纪桥亭子组伊利石-绢云母凝灰质细砂岩(H03);c—奥陶纪黄隘组凝灰质细-粉砂岩(H08);d—寒武纪边溪组凝灰质细砂岩(H09);Q—石英;Ser—绢云母;Ill—伊利石

Fig.2 Microscopic photos of Cambrian and Ordovician clastic sedimentary rocks in southern Hunan-northeastern Guangxi (crossed nicols, x5)

a-Sericite fine tuffaceous sandstone from Ordovician Tianmashan Formation (H06); b-Illite-sericite tuffaceous sandstone from Ordovician Qiaotingzi Formation (H03); c-Tuffaceous fine-siltstone from Ordovician Huangai Formation (H08); d-Tuffaceous sandstone from Cambrian Bianxi Formation (H09)

Q-Quartz; Ser-Sericite; Ill-Illite

距离较近,为近源沉积。

2 样品分析方法

样品在河北廊坊诚信地质服务有限公司进行粉碎,并用人工重砂法从样品中分选出锆石。其后工作均在中国地质大学(武汉)显微镜室和地质过程与矿产资源国家重点实验室完成。锆石CL阴极发光图片拍摄所使用仪器为JXA-8100电子探针,U-Pb同位素定年和微量元素含量分析利用LA-ICP-MS同时完成。激光剥蚀系统为193 mm Geolas 2005,ICP-MS为Agilent 7700a,激光剥蚀中采用氦气作为载气、氩气作为补偿气以调节灵敏度。激光剥蚀方式为单点剥蚀,直径为32 μm,时间分析数据包括20 s的空白信号和35 s的分析信号。分析仪器校正采用标准参考物质SRM610,数据年龄以国际标准锆石91500为外标。对数据的离线处理使用了软件ICPMSDataCal8.3[39, 40],普通Pb校正采用Andersen的方法进行[41]。单个数据点的误差均为1σ,样品年龄加权平均值的误差为2σ,锆石样品的U-Pb年龄谐和图绘制和年龄权重平均计算均采用Ludwig的Isoplot程序完成[42]。

大量的研究数据证明,当年龄<1000 Ma时,$^{206}Pb/^{238}U$的年龄精度高于$^{207}Pb/^{206}Pb$的年龄精度;当年龄>1000 Ma时,$^{207}Pb/^{206}Pb$比值受Pb丢失影响小,保持稳定,故以$^{207}Pb/^{206}Pb$的年龄作为锆石结晶年龄[43]。在本文中,对于<1000 Ma的锆石,选择$^{206}Pb/^{238}U$年龄做分析,对于>1000 Ma的锆石选择$^{207}Pb/^{206}Pb$年龄做分析,同时对于谐和度<90%或>110%的

数据,视为不和谐,不参与下文讨论。

3　分析结果与解释

研究区寒武纪和奥陶纪沉积岩中含有大量碎屑锆石,锆石多为无色透明,晶形较完整,形态上多呈长柱状,粒径50~250 μm,长宽比1∶1~3∶1,多具有一定程度的磨圆。锆石阴极发光(CL)图像见图3,图中标出了部分代表性锆石分析点的序号和表面年龄。CL图像显示,大部分锆石自形程度较高,具有明显的震荡环带,显示岩浆锆石特征,部分锆石具有薄的增生边,少部分锆石具有残留核,反映锆石成因具有多样性。4件样品共测试锆石252粒,得到有效年龄239组,测试结果见表1,碎屑锆石U-Pb年龄谐和图和年龄频率直方图见图4。

本次测试239个有效锆石点,Th/U比值分布范围为0.019~3.413,其中74%的Th/U比值大于0.4,且锆石自形程度较高,具有明显震荡环带,显示岩浆成因锆石特征[44, 45]。

对采自寒武纪地层样品H09中60粒锆石进行了U-Pb年龄测试。在锆石U-Pb年龄谐和图上,所有分析点均落在谐和线上或其附近,这些谐和线上的锆石年龄即可代表其真实形成年龄,少数数据投影点偏离谐和线,它们的真实年龄应老于$^{206}Pb/^{207}Pb$表面年龄[46]。U-Pb年龄值分布于3146~474 Ma,数据年龄变化区间较大,说明岩石中的锆石是多源的,包含了丰富的古地质构造-岩浆事件信息。H09样品年龄主要集中在5个时间段,分别为:2633~2473 Ma、1880~1521 Ma、1146~911 Ma、896~848 Ma、536~474 Ma,其中有58.3%的数据落在1146~911 Ma时间段,这与全球Grenville造山运动时间一致,反映Grenville造山事件对研究区及邻区影响较大。此外,在每个时间段内都具有一个或多个峰值,可能反映相应时间段内发生过构造-岩浆事件。值得注意的是,在这些数据中存在两组大于3000 Ma的年龄数据,$^{206}Pb/^{207}Pb$年龄分别是(3040±32)Ma和(3146±39)Ma,这两粒锆石磨圆度较高,反映经历了较远距离的搬运;锆石震荡环带明显,分析点均位于环带边缘,表明该锆石源区存在太古宙时期岩浆作用信息,这可以为研究华夏地块太古宙历史提供依据。

对采自奥陶纪地层样品H06、H03、H08中192粒锆石进行了U-Pb年龄测试,得到有效年龄数据179组,在锆石U-Pb年龄谐和图上,所有分析点均落在谐和线上或其附近。3件样品年龄变化区间均较宽:H06:3602~518 Ma;H03:3243~523 Ma;H08:2902~502 Ma,年龄分布特征相似,都主要分布于2600~2100 Ma、1800~1500 Ma、1200~900 Ma、900~700 Ma、700~500 Ma这五个时间段内。其中均以

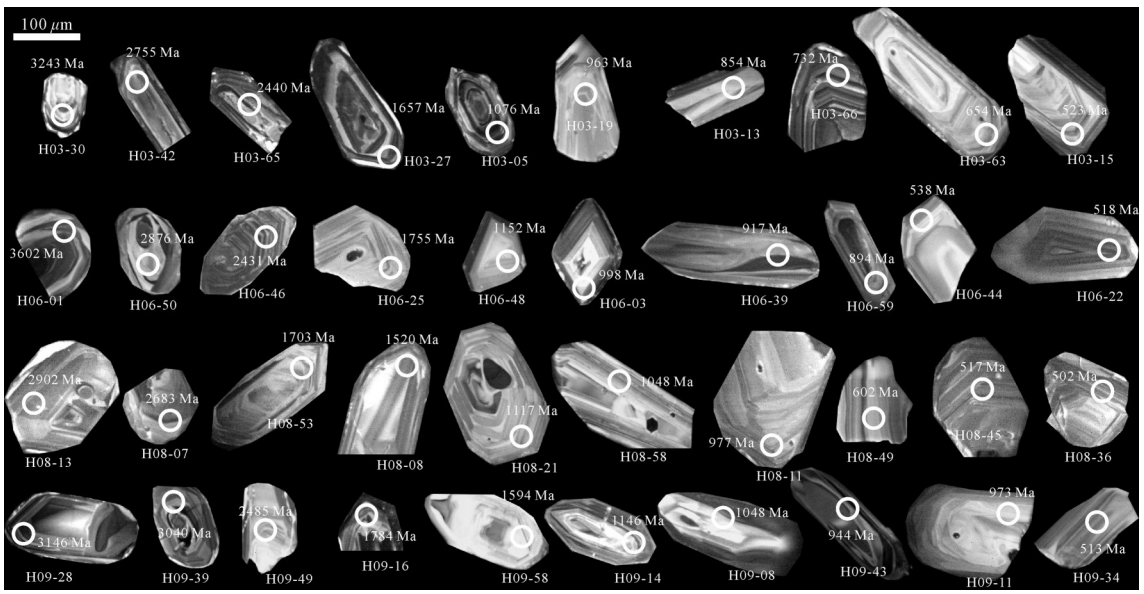

图3　湘南—桂东北地区寒武纪及奥陶纪沉积岩中部分碎屑锆石CL图像

Fig.3　Feature of partially detrital zircons (CL) of Cambrian and Ordovician in south Hunan −northeast Guangxi area

表1 湘南—桂东北地区寒武纪及奥陶纪沉积岩中碎屑锆石U-Th-Pb同位素分析

Table 1 U-Th-Pb isotopic analyses for the detrital zircons of Cambrian and Ordovician in southern Hunan -northeastern Guangxi area

分析点号	Th/U	同位素比值						表面年龄/Ma						谐和度
		$^{207}Pb/^{206}Pb$	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	
H06（O_3t）绢云母凝灰质细砂岩 带*号为变质锆石														
H06-01	0.25	0.3268	0.0070	34.1523	0.7804	0.7530	0.0083	3602	33	3614	23	3618	31	99%
H06-02	0.43	0.0720	0.0021	1.6697	0.0508	0.1671	0.0021	987	57	997	19	996	12	99%
H06-03	0.81	0.0710	0.0024	1.6394	0.0546	0.1674	0.0024	967	69	985	21	998	13	98%
H06-04	0.49	0.0733	0.0020	1.6611	0.0446	0.1633	0.0016	1033	54	994	17	975	9	98%
H06-05	1.07	0.0676	0.0038	1.1204	0.0657	0.1202	0.0022	857	112	763	31	732	13	95%
H06-06	0.71	0.1074	0.0029	4.6302	0.1232	0.3106	0.0032	1767	50	1755	22	1744	16	99%
H06-07	1.08	0.0683	0.0023	1.1888	0.0395	0.1251	0.0014	877	69	795	18	760	8	95%
H06-08	0.10	0.0695	0.0017	1.4719	0.0358	0.1524	0.0016	922	52	919	15	914	9	99%
H06-09	0.19	0.0727	0.0017	1.7163	0.0398	0.1695	0.0016	1006	44	1015	15	1009	9	99%
H06-10	0.37	0.0733	0.0021	1.7134	0.0475	0.1678	0.0016	1020	57	1014	18	1000	9	98%
H06-11	1.38	0.0687	0.0022	1.4821	0.0463	0.1552	0.0019	900	60	923	19	930	11	99%
H06-12	0.17	0.0732	0.0021	1.6854	0.0482	0.1649	0.0019	1020	58	1003	18	984	11	98%
H06-13	0.28	0.0604	0.0025	0.8470	0.0350	0.1006	0.0016	620	89	623	19	618	9	99%
H06-14	0.78	0.1593	0.0036	10.2111	0.2280	0.4600	0.0048	2450	38	2454	21	2440	21	99%
II06-15	0.94	0.0795	0.0028	2.1229	0.0714	0.1935	0.0025	1187	70	1156	23	1140	13	98%
H06-16	0.45	0.0661	0.0022	1.1944	0.0393	0.1302	0.0013	809	69	798	18	789	7	98%
H06-17	0.44	0.0993	0.0028	3.7156	0.1061	0.2705	0.0030	1613	49	1575	23	1543	15	97%
H06-18	0.28	0.2023	0.0051	15.0096	0.4603	0.5324	0.0080	2856	42	2816	29	2751	34	97%
H06-19	0.80	0.1302	0.0034	6.8926	0.1808	0.3832	0.0042	2102	46	2098	23	2091	19	99%
H06-20	0.46	0.0755	0.0033	1.7072	0.0734	0.1656	0.0023	1081	89	1011	28	988	13	97%
H06-21	1.87	0.0572	0.0025	0.6624	0.0279	0.0839	0.0011	498	96	516	17	520	7	99%
H06-22	2.39	0.0583	0.0028	0.6757	0.0333	0.0836	0.0012	543	104	524	20	518	7	98%
H06-23*	0.48	0.1647	0.0043	10.9753	0.2925	0.4789	0.0059	2506	43	2521	25	2523	26	99%
H06-24	0.81	0.0916	0.0049	2.0133	0.1015	0.1599	0.0024	1461	106	1120	34	956	13	84%
H06-25	1.13	0.1074	0.0040	4.6374	0.1731	0.3117	0.0050	1755	69	1756	31	1749	25	99%
H06-26	2.94	0.0579	0.0028	0.6803	0.0340	0.0842	0.0012	524	106	527	21	521	7	98%
H06-27	1.22	0.0757	0.0027	1.9274	0.0648	0.1838	0.0021	1087	75	1091	22	1088	11	99%
H06-28	0.48	0.0720	0.0024	1.6372	0.0541	0.1646	0.0018	987	70	985	21	982	10	99%
H06-29	0.18	0.0734	0.0021	1.7518	0.0508	0.1724	0.0018	1033	58	1028	19	1025	10	99%
H06-30*	0.12	0.1658	0.0043	10.6608	0.2890	0.4633	0.0047	2516	44	2494	25	2454	21	98%
H06-31	0.64	0.0625	0.0019	0.9402	0.0288	0.1085	0.0011	692	63	673	15	664	6	98%
H06-32	0.63	0.1366	0.0035	7.6422	0.2002	0.4050	0.0047	2184	45	2190	24	2192	22	99%
H06-33	1.13	0.1342	0.0030	7.4710	0.1762	0.4011	0.0041	2154	38	2170	21	2174	19	99%
H06-34*	1.21	0.0783	0.0023	2.0874	0.0578	0.1938	0.0021	1154	58	1145	19	1142	12	99%
H06-35	0.72	0.0709	0.0016	1.5311	0.0373	0.1558	0.0016	954	47	943	15	933	9	98%
H06-36	0.86	0.0634	0.0032	1.0500	0.0512	0.1207	0.0018	724	107	729	25	734	10	99%
H06-37	0.36	0.1078	0.0027	4.7141	0.1206	0.3157	0.0036	1765	46	1770	21	1769	18	99%
H06-38*	0.59	0.0711	0.0017	1.6192	0.0375	0.1642	0.0016	961	44	978	15	980	9	99%
H06-39	0.21	0.0683	0.0018	1.4503	0.0421	0.1529	0.0020	877	56	910	17	917	11	99%
H06-40*	1.01	0.0868	0.0027	2.8542	0.0949	0.2371	0.0038	1367	61	1370	25	1371	20	99%

续表1

分析点号	Th/U	同位素比值						表面年龄/Ma						谐和度
		$^{207}Pb/^{206}Pb$	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	
H06-41	1.22	0.0778	0.0025	2.3338	0.0779	0.2166	0.0027	1140	65	1223	24	1264	15	96%
H06-42	0.52	0.0702	0.0027	1.5657	0.0563	0.1625	0.0021	1000	78	957	22	971	12	98%
H06-43	0.50	0.0681	0.0063	0.9622	0.0758	0.1112	0.0026	872	158	684	39	679	15	99%
H06-44	2.04	0.0590	0.0036	0.6974	0.0398	0.0870	0.0015	569	134	537	24	538	9	99%
H06-45	0.80	0.0754	0.0048	1.2186	0.0763	0.1182	0.0021	1080	128	809	35	720	12	88%
H06-46	0.66	0.1576	0.0035	8.9272	0.1988	0.4061	0.0037	2431	43	2331	20	2197	17	94%
H06-47	0.72	0.0636	0.0038	1.0993	0.0649	0.1266	0.0022	728	129	753	31	768	12	97%
H06-48	0.63	0.0782	0.0033	2.0742	0.0840	0.1915	0.0027	1152	85	1140	28	1129	14	99%
H06-49	0.39	0.0735	0.0028	1.5226	0.0618	0.1481	0.0025	1029	76	940	25	890	14	94%
H06-50*	0.17	0.2062	0.0047	15.0155	0.3984	0.5189	0.0080	2876	37	2816	25	2695	34	95%
H06-51	2.17	0.0756	0.0020	1.4434	0.0369	0.1364	0.0012	1085	52	907	15	824	7	90%
H06-52	0.98	0.0874	0.0028	1.7547	0.0592	0.1437	0.0026	1370	61	1029	22	866	14	82%
H06-53	0.45	0.2041	0.0049	13.4212	0.2809	0.4741	0.0052	2859	39	2710	20	2502	23	92%
H06-54	0.68	0.1004	0.0019	2.5317	0.0472	0.1804	0.0014	1632	34	1281	14	1069	7	81%
H06-55	0.99	0.1355	0.0021	5.7895	0.0960	0.3064	0.0023	2172	27	1945	14	1723	11	87%
H06-56	0.73	0.1030	0.0018	2.5046	0.0426	0.1746	0.0011	1680	27	1273	12	1037	6	79%
H06-57	0.66	0.0832	0.0029	1.6749	0.0587	0.1446	0.0015	1276	69	999	22	871	8	86%
H06-58	0.81	0.0794	0.0048	1.0814	0.0648	0.0993	0.0014	1183	120	744	32	610	8	80%
H06-59	0.47	0.0784	0.0041	1.5920	0.0780	0.1487	0.0019	1158	103	967	31	894	11	92%
H06-60	0.91	0.0868	0.0024	2.0352	0.0554	0.1689	0.0016	1367	54	1127	19	1006	9	88%
H03（$O_{1-2}q$）伊利石-绢云母凝灰质细砂岩 带*号为变质锆石														
H03-01	0.57	0.1683	0.0053	7.5247	0.2597	0.3197	0.0034	2540	52	2176	31	1788	17	80%
H03-02	0.09	0.0735	0.0016	1.7521	0.0367	0.1713	0.0014	1029	44	1028	14	1019	8	99%
H03-03	0.32	0.0614	0.0013	0.9368	0.0228	0.1096	0.0014	654	46	671	12	671	8	99%
H03-04*	0.80	0.0711	0.0016	1.6062	0.0372	0.1625	0.0016	959	42	973	15	971	9	99%
H03-05	0.93	0.0753	0.0018	1.8420	0.0448	0.1761	0.0016	1076	49	1061	16	1045	9	98%
H03-06	0.55	0.1060	0.0064	2.1365	0.1512	0.1397	0.0026	1731	111	1161	49	843	14	68%
H03-07	0.84	0.0572	0.0018	0.6756	0.0211	0.0852	0.0009	498	69	524	13	527	6	99%
H03-08	0.87	0.0766	0.0027	2.0841	0.0765	0.1954	0.0023	1122	71	1144	25	1151	13	99%
H03-09	0.19	0.0704	0.0016	1.5681	0.0360	0.1605	0.0016	943	47	958	14	959	9	99%
H03-10	0.77	0.1590	0.0035	10.1091	0.2159	0.4584	0.0047	2456	37	2445	20	2432	21	99%
H03-11	0.13	0.0622	0.0016	0.9632	0.0247	0.1116	0.0011	680	56	685	13	682	6	99%
H03-12	0.54	0.1033	0.0027	4.2359	0.1082	0.2954	0.0031	1684	48	1681	21	1668	16	99%
H03-13	0.84	0.0665	0.0022	1.3078	0.0426	0.1416	0.0015	833	75	849	19	854	9	99%
H03-14	0.85	0.1611	0.0037	10.3822	0.2309	0.4635	0.0046	2478	38	2469	21	2455	20	99%
H03-15	1.03	0.0581	0.0023	0.6802	0.0270	0.0845	0.0010	600	89	527	16	523	6	99%
H03-16	0.21	0.1598	0.0033	8.3176	0.1735	0.3739	0.0037	2453	35	2266	19	2048	17	89%
H03-17	0.22	0.1157	0.0025	5.6024	0.1281	0.3483	0.0050	1900	38	1916	20	1927	24	99%
H03-18	0.64	0.0670	0.0027	1.2746	0.0522	0.1368	0.0020	839	85	834	23	826	11	99%
H03-19	0.87	0.0726	0.0033	1.6164	0.0710	0.1612	0.0021	1011	93	977	28	963	12	98%
H03-20*	3.41	0.1629	0.0038	10.8047	0.2527	0.4767	0.0059	2486	39	2506	22	2513	26	99%

续表1

分析点号	Th/U	同位素比值						表面年龄/Ma						谐和度
		$^{207}Pb/^{206}Pb$	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	
H03-21	1.03	0.0634	0.0025	0.7988	0.0302	0.0909	0.0011	720	282	596	17	561	7	93%
H03-22	0.71	0.0568	0.0015	0.6840	0.0179	0.0864	0.0008	483	55	529	11	534	5	99%
H03-23	0.72	0.0736	0.0039	1.5535	0.0950	0.1511	0.0029	1031	112	952	38	907	16	95%
H03-24	0.63	0.0620	0.0022	1.0292	0.0358	0.1191	0.0014	676	76	719	18	726	8	99%
H03-25	0.55	0.0789	0.0024	1.8258	0.0574	0.1654	0.0020	1172	61	1055	21	987	11	93%
H03-26	1.43	0.1155	0.0032	4.9622	0.1343	0.3091	0.0042	1888	50	1813	23	1736	20	95%
H03-27	0.44	0.1018	0.0024	4.3512	0.0974	0.3066	0.0030	1657	43	1703	18	1724	15	98%
H03-28	0.04	0.0868	0.0025	2.2351	0.0919	0.1794	0.0039	1355	56	1192	29	1064	21	88%
H03-29	0.75	0.0782	0.0022	2.1711	0.0611	0.1990	0.0021	1154	57	1172	20	1170	11	99%
H03-30	0.61	0.2594	0.0069	22.5409	0.5821	0.6238	0.0068	3243	158	3207	25	3125	27	97%
H03-31	0.45	0.0745	0.0030	1.8664	0.0702	0.1818	0.0025	1057	86	1069	25	1077	14	99%
H03-32	0.64	0.1018	0.0024	3.6135	0.0936	0.2544	0.0030	1657	44	1553	21	1461	15	93%
H03-33	0.97	0.0987	0.0024	3.7071	0.0928	0.2699	0.0026	1600	51	1573	20	1540	13	97%
H03-34	0.67	0.1103	0.0025	5.0593	0.1211	0.3300	0.0036	1806	42	1829	20	1838	18	99%
H03-35	1.10	0.0795	0.0026	1.8344	0.0668	0.1657	0.0022	1187	66	1058	24	988	12	93%
H03-36	0.76	0.1207	0.0027	6.0254	0.1407	0.3601	0.0042	1969	39	1980	20	1983	20	99%
H03-37	1.06	0.1658	0.0037	10.9864	0.2516	0.4784	0.0049	2517	38	2522	21	2520	21	99%
H03-38	1.01	0.0931	0.0032	3.2976	0.1125	0.2565	0.0033	1500	60	1480	27	1472	17	99%
H03-39	0.66	0.0986	0.0025	3.8742	0.0999	0.2836	0.0029	1598	53	1608	21	1610	15	99%
H03-40	0.50	0.0796	0.0019	2.1729	0.0521	0.1969	0.0018	1188	47	1172	17	1159	10	98%
H03-41	0.33	0.0701	0.0020	1.5831	0.0474	0.1627	0.0019	931	59	964	19	972	11	99%
H03-42	0.57	0.1915	0.0046	14.1918	0.3395	0.5345	0.0050	2755	40	2763	23	2761	21	99%
H03-43	0.74	0.0839	0.0025	2.1345	0.0624	0.1838	0.0020	1300	59	1160	20	1088	11	93%
H03-44	0.07	0.0691	0.0030	1.3267	0.0527	0.1399	0.0018	902	89	857	23	844	10	98%
H03-45	0.82	0.1674	0.0036	11.2088	0.2504	0.4819	0.0050	2532	37	2541	21	2536	22	99%
H03-46	0.53	0.0718	0.0025	1.6401	0.0543	0.1648	0.0016	981	70	986	21	984	9	99%
H03-47	0.61	0.0706	0.0020	1.3365	0.0383	0.1359	0.0014	946	62	862	17	821	8	95%
H03-48*	0.15	0.1314	0.0033	6.3363	0.1563	0.3465	0.0032	2117	44	2023	22	1918	15	94%
H03-49	0.58	0.1048	0.0029	4.1060	0.1133	0.2817	0.0027	1722	52	1655	23	1600	14	96%
H03-50	0.68	0.2077	0.0057	16.0266	0.4394	0.5575	0.0063	2887	45	2878	26	2856	26	99%
H03-51	1.26	0.0711	0.0024	1.5649	0.0524	0.1593	0.0018	961	64	956	21	953	10	99%
H03-52	0.82	0.0684	0.0032	1.1683	0.0546	0.1246	0.0017	880	94	786	26	757	10	96%
H03-53	0.78	0.1654	0.0036	9.6897	0.2267	0.4236	0.0042	2522	37	2406	22	2277	19	94%
H03-54	0.46	0.0708	0.0035	1.4502	0.0689	0.1499	0.0019	952	97	910	29	901	11	98%
H03-55	0.97	0.0682	0.0022	1.4021	0.0466	0.1491	0.0017	876	69	890	20	896	10	99%
H03-56*	0.08	0.0742	0.0017	1.3273	0.0316	0.1292	0.0012	1056	41	858	14	783	7	90%
H03-57	0.29	0.0815	0.0019	2.4311	0.0591	0.2156	0.0023	1235	46	1252	18	1258	12	99%
H03-58	0.12	0.0777	0.0018	2.1781	0.0537	0.2024	0.0023	1139	44	1174	17	1188	12	98%
H03-59	1.50	0.0644	0.0019	1.1668	0.0338	0.1307	0.0013	767	61	785	16	792	8	99%
H03-60	0.77	0.0785	0.0025	2.0385	0.0634	0.1872	0.0023	1159	63	1128	21	1106	12	98%

续表1

分析点号	Th/U	同位素比值						表面年龄/Ma						谐和度
		$^{207}Pb/^{206}Pb$	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	
H03-61*	0.28	0.0728	0.0019	1.7413	0.0452	0.1721	0.0017	1009	54	1024	17	1024	9	99%
H03-62	0.52	0.0644	0.0026	1.1629	0.0475	0.1303	0.0017	754	52	783	22	789	10	99%
H03-63	0.29	0.0685	0.0031	1.0184	0.0487	0.1068	0.0016	883	93	713	24	654	9	91%
H03-64	0.37	0.0637	0.0023	1.3654	0.0482	0.1555	0.0020	731	78	874	21	932	11	93%
H03-65	1.11	0.1585	0.0038	10.1598	0.2409	0.4605	0.0045	2440	41	2449	22	2442	20	99%
H03-66	0.23	0.0626	0.0020	1.0475	0.0339	0.1202	0.0013	694	65	728	17	732	7	99%
H08（O_1h）凝灰质细-粉砂岩 带*号为变质锆石														
H08-01	2.50	0.0595	0.0018	0.7601	0.0229	0.0921	0.0010	583	67	574	13	568	6	98%
H08-02	0.14	0.0748	0.0017	1.8346	0.0431	0.1765	0.0020	1065	46	1058	15	1048	11	99%
H08-03	0.66	0.0713	0.0030	1.6332	0.0687	0.1654	0.0022	969	85	983	26	986	12	99%
H08-04*	0.74	0.0695	0.0025	1.4994	0.0533	0.1558	0.0019	922	74	930	22	934	11	99%
H08-05	0.44	0.0585	0.0021	0.7568	0.0273	0.0936	0.0011	550	75	572	16	577	7	99%
H08-06	0.32	0.0966	0.0030	3.7105	0.1171	0.2768	0.0034	1559	57	1574	25	1575	17	99%
H08-07*	0.43	0.1832	0.0047	13.1705	0.3610	0.5178	0.0065	2683	43	2692	26	2690	28	99%
H08-08	0.20	0.0945	0.0022	3.5233	0.0867	0.2689	0.0032	1520	44	1532	19	1535	16	99%
H08-09	0.84	0.1063	0.0021	4.5237	0.0923	0.3069	0.0024	1736	36	1735	17	1726	12	99%
H08-10	1.13	0.0583	0.0015	0.7287	0.0197	0.0904	0.0010	543	57	556	12	558	6	99%
H08-11	0.54	0.0756	0.0022	1.7290	0.0592	0.1636	0.0019	1083	53	1019	22	977	10	95%
H08-12	0.33	0.0752	0.0032	2.0213	0.0839	0.1974	0.0029	1074	90	1123	28	1161	16	96%
H08-13	0.84	0.2096	0.0015	16.7099	0.1665	0.5769	0.0039	2902	11	2918	10	2936	16	99%
H08-14	0.61	0.0585	0.0014	0.6973	0.0177	0.0862	0.0008	550	58	537	11	533	5	99%
H08-15	0.68	0.0707	0.0019	1.5543	0.0410	0.1591	0.0015	950	58	952	16	952	8	99%
H08-16	0.38	0.0625	0.0027	1.3616	0.0562	0.1598	0.0026	692	94	873	24	956	14	90%
H08-17	1.27	0.0951	0.0025	3.6733	0.1016	0.2782	0.0035	1529	49	1566	22	1582	18	98%
H08-18	1.61	0.0689	0.0032	1.3142	0.0580	0.1384	0.0020	895	94	852	25	836	11	98%
H08-19	1.41	0.0552	0.0033	0.6359	0.0385	0.0838	0.0014	420	135	500	24	519	8	96%
H08-20	0.18	0.0785	0.0019	2.1408	0.0516	0.1955	0.0018	1161	42	1162	17	1151	10	99%
H08-21	0.52	0.0768	0.0023	2.0216	0.0580	0.1899	0.0021	1117	61	1123	19	1121	12	99%
H08-22	0.30	0.0611	0.0025	0.8729	0.0372	0.1024	0.0013	643	87	637	20	628	7	98%
H08-23	0.50	0.0776	0.0036	2.0769	0.0938	0.1935	0.0032	1139	93	1141	31	1140	17	99%
H08-24	1.02	0.1847	0.0056	13.1938	0.3815	0.5129	0.0060	2695	45	2694	27	2669	26	99%
H08-25	0.49	0.0710	0.0029	1.5351	0.0600	0.1558	0.0021	967	83	945	24	934	12	98%
H08-26	0.63	0.1277	0.0032	6.3604	0.1553	0.3569	0.0032	2078	44	2027	21	1968	15	97%
H08-27	0.39	0.0985	0.0025	3.4232	0.0867	0.2498	0.0023	1595	48	1510	20	1437	12	95%
H08-28	0.71	0.0779	0.0026	2.0367	0.0668	0.1885	0.0019	1146	67	1128	22	1114	10	98%
H08-29	0.37	0.0662	0.0021	1.1920	0.0378	0.1299	0.0014	813	68	797	18	787	8	98%
H08-30	0.58	0.0921	0.0024	3.2150	0.0827	0.2515	0.0024	1469	49	1461	20	1446	12	98%
H08-31	0.67	0.1690	0.0046	11.0746	0.3124	0.4722	0.0053	2548	46	2529	26	2493	23	98%

续表1

分析点号	Th/U	同位素比值						表面年龄/Ma						谐和度
		$^{207}Pb/^{206}Pb$	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	
H08-34	0.47	0.0773	0.0017	1.9315	0.0466	0.1793	0.0018	1131	44	1092	16	1063	10	97%
H08-35	1.51	0.0617	0.0041	0.6814	0.0432	0.0821	0.0016	661	139	528	26	509	10	96%
H08-36	1.26	0.0566	0.0023	0.6361	0.0268	0.0809	0.0011	476	91	500	17	502	7	99%
H08-37	0.23	0.1303	0.0032	5.7807	0.1420	0.3181	0.0036	2103	42	1944	21	1780	18	91%
H08-38	0.56	0.0689	0.0028	1.4342	0.0573	0.1501	0.0020	898	83	903	24	902	11	99%
H08-39	0.12	0.1091	0.0023	4.6588	0.0958	0.3060	0.0027	1787	44	1760	17	1721	13	97%
H08-40	0.52	0.0932	0.0021	3.1945	0.0699	0.2454	0.0023	1491	41	1456	17	1415	12	97%
H08-41	0.79	0.0716	0.0034	1.3349	0.0633	0.1348	0.0023	976	97	861	28	815	13	94%
H08-42*	0.36	0.1656	0.0043	11.1738	0.3093	0.4819	0.0075	2514	43	2538	26	2535	33	99%
H08-43	0.20	0.0845	0.0026	2.4357	0.0755	0.2058	0.0026	1306	59	1253	22	1206	14	96%
H08-44*	1.21	0.0705	0.0024	1.5724	0.0538	0.1601	0.0021	943	69	959	21	957	12	99%
H08-45	1.19	0.0567	0.0018	0.6599	0.0208	0.0836	0.0009	480	70	515	13	517	5	99%
H08-46	0.57	0.0759	0.0019	1.9360	0.0472	0.1828	0.0018	1094	50	1094	16	1083	10	98%
H08-47	1.27	0.0582	0.0032	0.6776	0.0370	0.0840	0.0013	539	120	525	22	520	8	98%
H08-48	0.74	0.1025	0.0029	4.2332	0.1204	0.2967	0.0035	1670	52	1680	23	1675	17	99%
H08-49	2.07	0.0651	0.0040	0.8522	0.0492	0.0980	0.0019	776	130	626	27	602	11	96%
H08-50*	0.43	0.1446	0.0033	8.1174	0.1776	0.4026	0.0034	2283	39	2244	20	2181	15	97%
H08-51	1.19	0.0659	0.0024	1.2373	0.0451	0.1351	0.0016	1200	76	818	20	817	9	99%
H08-52	0.63	0.0769	0.0027	1.9082	0.0658	0.1789	0.0023	1120	70	1084	23	1061	12	97%
H08-53	0.60	0.1044	0.0030	4.2296	0.1161	0.2910	0.0032	1703	52	1680	23	1646	16	97%
H08-54	0.74	0.0727	0.0041	1.6023	0.0866	0.1622	0.0027	1006	115	971	34	969	15	99%
H08-55	0.27	0.0741	0.0023	1.7900	0.0539	0.1734	0.0018	1044	58	1042	20	1031	10	98%
H08-56	1.96	0.0597	0.0039	0.7270	0.0452	0.0906	0.0018	594	136	555	27	559	11	99%
H08-57	0.87	0.0646	0.0029	1.1570	0.0491	0.1299	0.0017	761	94	781	23	787	10	99%
H08-58	0.40	0.0742	0.0033	1.7523	0.0750	0.1718	0.0028	1048	89	1028	28	1022	15	99%
H08-59	0.48	0.0611	0.0014	0.8735	0.0203	0.1032	0.0012	643	53	637	11	633	7	99%
H08-60	0.96	0.0576	0.0023	0.7652	0.0301	0.0964	0.0013	522	82	577	17	593	8	97%
H08-61	0.70	0.1025	0.0028	4.1849	0.1174	0.2954	0.0034	1670	52	1671	23	1668	17	99%
H08-62	0.74	0.0717	0.0023	1.6588	0.0563	0.1670	0.0021	989	60	993	21	996	12	99%
H08-63	0.62	0.1007	0.0032	4.0064	0.1321	0.2888	0.0047	1636	59	1635	27	1636	23	99%
H08-64	0.66	0.0862	0.0016	2.7242	0.0554	0.2278	0.0020	1343	42	1335	15	1323	10	99%
H08-65	0.25	0.0658	0.0015	1.1576	0.0267	0.1270	0.0011	1200	48	781	13	771	6	98%
H08-66	0.69	0.0991	0.0021	3.9293	0.0880	0.2861	0.0028	1607	39	1620	18	1622	14	99%
H09（∈ *b*）凝灰质细砂岩 带*号为变质锆石														
H09-01	1.50	0.0754	0.0037	1.7187	0.0813	0.1659	0.0025	1080	94	1016	30	989	14	97%
H09-02	0.47	0.0707	0.0020	1.5591	0.0425	0.1591	0.0017	950	53	954	17	952	9	99%
H09-03	0.61	0.0773	0.0017	1.7367	0.0372	0.1612	0.0014	1128	44	1022	14	964	8	94%
H09-04*	0.89	0.0731	0.0024	1.7747	0.0592	0.1743	0.0021	1018	67	1036	22	1036	11	99%
H09-05	0.37	0.0683	0.0021	1.4789	0.0434	0.1557	0.0017	877	63	922	18	933	9	98%

续表1

分析点号	Th/U	同位素比值						表面年龄/Ma						谐和度
		$^{207}Pb/^{206}Pb$	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	
H09-06	1.75	0.0564	0.0025	0.6271	0.0276	0.0800	0.0011	478	98	494	17	496	6	99%
H09-07	0.64	0.0677	0.0020	1.3715	0.0377	0.1460	0.0020	857	60	877	16	879	11	99%
H09-08	0.73	0.0742	0.0032	2.0005	0.0829	0.1948	0.0026	1048	85	1116	28	1147	14	97%
H09-09	0.42	0.0736	0.0021	1.7776	0.0497	0.1740	0.0019	1031	57	1037	18	1034	10	99%
H09-10*	1.32	0.0774	0.0030	1.9832	0.0702	0.1870	0.0028	1131	76	1110	24	1105	15	99%
H09-11	0.74	0.0728	0.0026	1.6374	0.0589	0.1630	0.0023	1009	40	985	23	973	13	98%
H09-12	0.33	0.1617	0.0038	9.9434	0.2361	0.4429	0.0044	2473	44	2430	22	2363	20	97%
H09-13	1.64	0.0582	0.0029	0.6503	0.0310	0.0812	0.0012	600	103	509	19	503	7	98%
H09-14	0.36	0.0779	0.0020	2.0801	0.0546	0.1926	0.0021	1146	52	1142	18	1135	11	99%
H09-15	0.62	0.0971	0.0026	3.4193	0.0933	0.2538	0.0026	1569	50	1509	21	1458	14	96%
H09-16	0.26	0.1090	0.0021	4.8067	0.0953	0.3172	0.0027	1784	37	1786	17	1776	13	99%
H09-17	0.67	0.1099	0.0028	4.9310	0.1226	0.3238	0.0036	1798	47	1808	21	1808	17	99%
H09-18	0.62	0.0720	0.0021	1.6549	0.0489	0.1655	0.0019	987	65	991	19	987	11	99%
H09-19	0.38	0.0729	0.0021	1.7902	0.0507	0.1768	0.0019	1009	92	1042	18	1049	10	99%
H09-20	0.80	0.0726	0.0028	1.7441	0.0646	0.1734	0.0021	1006	78	1025	24	1031	11	99%
H09-21*	0.19	0.0708	0.0031	1.3742	0.0567	0.1406	0.0017	954	90	878	24	848	10	96%
H09-22	0.74	0.0700	0.0021	1.5411	0.0459	0.1583	0.0018	928	62	947	18	947	10	99%
H09-23	1.70	0.0593	0.0023	0.6268	0.0237	0.0762	0.0010	576	79	494	15	474	6	95%
H09-24	2.67	0.0708	0.0022	1.5550	0.0484	0.1578	0.0020	954	65	952	19	944	11	99%
H09-25	0.39	0.0767	0.0022	2.0700	0.0571	0.1941	0.0026	1122	56	1139	19	1144	14	99%
H09-26	0.81	0.0679	0.0023	1.4088	0.0474	0.1491	0.0017	865	103	893	20	896	10	99%
H09-27	0.52	0.0687	0.0017	1.5192	0.0370	0.1589	0.0018	900	50	938	15	950	10	98%
H09-28	1.19	0.2438	0.0047	21.6126	0.4096	0.6363	0.0055	3146	31	3166	18	3175	22	99%
H09-29	0.08	0.0692	0.0017	1.4772	0.0364	0.1533	0.0015	906	50	921	15	919	8	99%
H09-30	0.65	0.0986	0.0025	3.8586	0.0948	0.2816	0.0030	1598	53	1605	20	1599	15	99%
H09-31*	0.16	0.0653	0.0018	1.3158	0.0359	0.1453	0.0019	783	57	853	16	874	11	97%
H09-32	1.02	0.0582	0.0037	0.6663	0.0390	0.0842	0.0014	600	169	518	24	521	8	99%
H09-33	0.08	0.0688	0.0016	1.5250	0.0365	0.1601	0.0016	900	48	940	15	957	9	98%
H09-34	1.41	0.0584	0.0030	0.6649	0.0345	0.0828	0.0011	543	110	518	21	513	7	99%
H09-35	0.51	0.0710	0.0018	1.6798	0.0429	0.1712	0.0014	967	53	1001	16	1019	8	98%
H09-36	0.51	0.0743	0.0021	1.8459	0.0550	0.1800	0.0021	1050	58	1062	20	1067	11	99%
H09-37	0.58	0.0703	0.0021	1.5766	0.0487	0.1623	0.0019	939	61	961	19	969	11	99%
H09-38	0.40	0.0695	0.0016	1.4894	0.0355	0.1550	0.0015	922	48	926	14	929	9	99%
H09-39	0.37	0.2282	0.0046	19.1814	0.4306	0.6056	0.0069	3040	32	3051	22	3052	28	99%
H09-40	0.94	0.0686	0.0021	1.4388	0.0432	0.1518	0.0017	887	64	905	18	911	9	99%
H09-41	0.58	0.1779	0.0045	12.3615	0.3212	0.5000	0.0054	2633	43	2632	24	2614	23	99%
H09-42	0.62	0.0715	0.0022	1.6048	0.0464	0.1621	0.0021	972	61	972	18	968	12	99%
H09-43	0.60	0.0703	0.0020	1.5472	0.0440	0.1578	0.0017	939	57	949	18	944	9	99%
H09-44*	0.02	0.0947	0.0020	3.4734	0.0716	0.2633	0.0023	1521	40	1521	16	1507	12	99%
H09-45	0.98	0.0730	0.0025	1.7689	0.0617	0.1737	0.0021	1015	70	1034	23	1033	11	99%
H09-46	0.52	0.0752	0.0017	1.8895	0.0421	0.1801	0.0015	1076	46	1077	15	1068	8	99%

续表1

分析点号	Th/U	同位素比值						表面年龄/Ma						谐和度
		$^{207}Pb/^{206}Pb$	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	
H09-47	0.07	0.0715	0.0021	1.6087	0.0477	0.1618	0.0018	972	61	974	19	967	10	99%
H09-48*	0.84	0.1004	0.0027	3.8074	0.1033	0.2723	0.0027	1631	46	1594	22	1552	14	97%
H09-49	0.93	0.1628	0.0045	10.5609	0.2970	0.4670	0.0055	2485	47	2485	26	2470	24	99%
H09-50	0.43	0.0581	0.0015	0.6988	0.0187	0.0867	0.0010	532	57	538	11	536	6	99%
H09-51	0.09	0.1032	0.0023	4.2900	0.0961	0.2996	0.0029	1683	40	1691	18	1689	14	99%
H09-52*	0.06	0.0719	0.0021	1.5738	0.0452	0.1582	0.0016	983	59	960	18	947	9	98%
H09-53	0.94	0.0737	0.0025	1.7633	0.0600	0.1737	0.0025	1033	67	1032	22	1033	14	99%
H09-54	0.75	0.0732	0.0025	1.7291	0.0590	0.1718	0.0023	1020	69	1019	22	1022	13	99%
H09-55	0.90	0.0726	0.0023	1.7061	0.0572	0.1696	0.0021	1003	63	1011	21	1010	11	99%
H09-56	0.20	0.0701	0.0019	1.6006	0.0438	0.1652	0.0017	931	54	970	17	986	9	98%
H09-57	0.35	0.0608	0.0028	0.8813	0.0405	0.1057	0.0013	632	101	642	22	648	8	99%
H09-58	0.53	0.0984	0.0031	3.8667	0.1261	0.2853	0.0041	1594	59	1607	26	1618	20	99%
H09-59	0.85	0.1149	0.0024	5.3973	0.1216	0.3393	0.0041	1880	38	1884	19	1883	20	99%
H09-60	0.25	0.0757	0.0018	1.9778	0.0471	0.1885	0.0019	1087	47	1108	16	1113	11	99%

1200~900 Ma年龄段的锆石年龄最多，H06占41.2%，H03占30.3%，H08占36.7%，反映Grenville造山期地质事件对研究区具有重大意义，Grenville期构造-岩浆事件可能为研究区奥陶纪地层提供主要物源。同时，3件样品锆石年龄频率直方图中出现多个相似的年龄峰值：520 Ma、790 Ma、990 Ma、1110 Ma、2120 Ma、2500 Ma、2890 Ma，可能反映3件样品具有相似的物源。

此外，奥陶纪地层3件样品均捕捉到了太古宙信息，共获得大于2500 Ma的数据18组。其中最老的年龄来是自于H06的锆石H06-01，年龄为3602 Ma，属始太古宙。由于华夏地块至今未有关于太古宙结晶基底的报道，推测可能来自华夏地块或扬子地块未出露的太古宙基底，当然也不排除来自曾经与华夏地块相邻的具有太古宙结晶基底大陆的可能性，具体成因尚待深入研究。同时，3件样品中均发现一定数量650~500 Ma的锆石，时间上与全球泛非事件对应，推测是全球泛非事件的年龄信息，反映华夏地块与冈瓦纳大陆可能具有亲缘性。

4 讨 论

沉积岩中的碎屑矿物（如锆石、石榴子石、磷灰石、白云石等）都曾被用于识别沉积物源区和反演古老大陆演化历史[18, 47]。其中锆石最为稳定，受岩石风化、剥蚀、搬运、分选和沉积过程影响小，其U-Th-Pb同位素体系封闭温度高，受后期构造热事件影响小，碎屑锆石年龄谱系特征可以直接反映沉积物源区年龄组成[48-51]。同时，碎屑锆石的年龄结构不受沉积循环分馏过程影响，即使锆石经历沉积再循环，其年龄特征也与区域构造-岩浆事件相对应[52]。

4.1 碎屑锆石年龄特征

4件样品中锆石年龄均在1200~900 Ma时间段出现最高峰，峰值为970 Ma左右，与全球Grenville造山期地质事件基本一致。目前，在华夏地块以及扬子地块南部都发现大量的Grenville造山期岩浆锆石年龄，如粤中和平县古寨花岗闪长岩中发现大量1070~910 Ma的锆石[46]；福建建瓯叶坑变石英角斑岩中发现(1100±19)Ma年的岩浆锆石[53]；江西永丰县潭头群变石英角斑岩锆石蒸发法$^{206}Pb/^{207}Pb$年龄为（1027±36）Ma[54]；戈阳铁砂街群变流纹岩中锆石U-Pb年龄为（1147±18）Ma [24]等。此外在粤中[55]、赣南[46]、广西东部大瑶山—大明山[56]、湘中大乘山[57]、湘东湘乡—醴陵和湘东南桂阳[34]、湘桂交界的苗儿山和湘南金鸡岭[35]等地区，沉积岩碎屑锆石中均发现大量Grenville造山期年龄。综合大量的锆石年龄数据，推测华南南部曾经存在一个Grenville造山带，为扬子和华夏地块接合带沉积区提供主要物源。

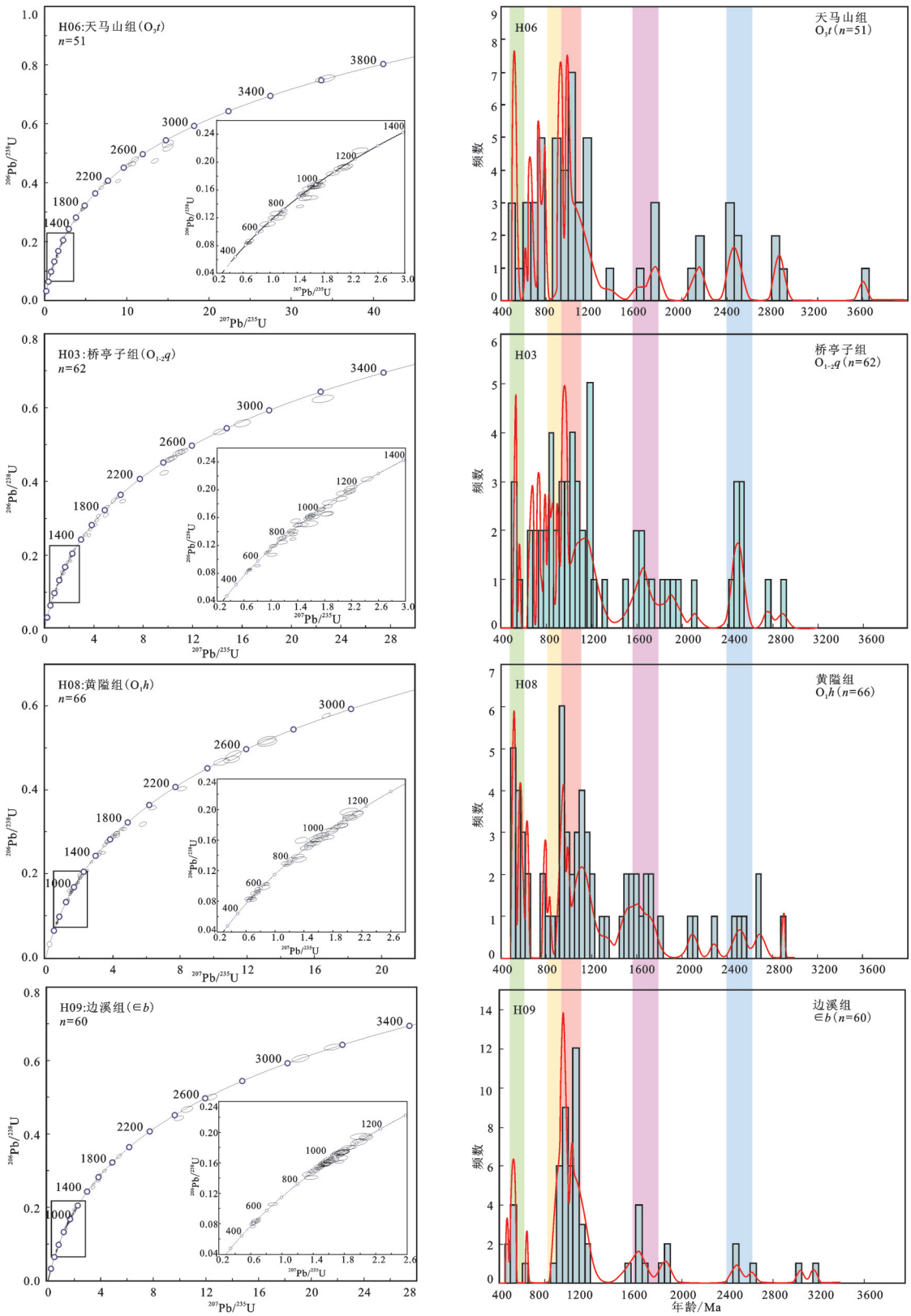

图4　湘南—桂东北地区寒武纪及奥陶纪沉积岩中碎屑锆石U-Pb年龄谐和图和年龄频率直方图

Fig.4　Zircon U-Pb concordia diagrams and histogram diagrams of Cambrian and Ordovician in southern Hunan − northeastern Guangxi area

本次测年数据次高峰值位于520 Ma左右，与全球泛非事件时间一致。泛非事件指大约(550±100) Ma前发生的一次重要的深成事件，是莫桑比克洋闭合，东、西冈瓦纳逐步聚合，并形成冈瓦纳大陆的过程[58, 59]。前人研究中也发现大量的泛非期碎屑锆石[34, 46]，同时在粤东和平县发现了(507±17)Ma的古寨岩体[60]，认为研究区受泛非事件影响比较显著。此外，Yang et al (2004)通过对古地磁数据分析，认为在晚新元古代—早古生代期间，华南应该位于澳大利亚东部或者位于澳大利亚西部与印度之间[61]；Metcalfe(2011)通过对比古生物分布特征，认为早古生代期间生物群是贯穿华南和印度—喜马拉雅的[62]；Jiang et al (2003)研究印度板块和扬子地块新元古代—早古生代地层，认为两者具有相似性[63]；Li et al (2014)和 Yao et al (2014)通过统计分析华夏地块及其他地块碎屑锆石形态特征，年龄谱分布特征，以及Hf同位素特征等，认为华夏地块寒武纪沉积岩碎屑锆石一部分来自印度北部，一部分来自华夏地块泛非期火成岩[13, 14]。本文的结果与Li et al (2014)和 Yao et al (2014)的研究结果对比，认为华夏地块与冈瓦纳大陆可能具有亲缘性，研究区寒武纪和奥陶纪地层中520 Ma左右的碎屑锆石可能有一部分来自Gandwana大陆时期与其相邻的印度北部，一部分来自华夏地块内部泛非期火成岩。

本次测试得到在900~700 Ma年龄段范围内的锆石也占很大一部分，在频率直方图上此年龄段形成一个较宽的峰，峰值位于800 Ma左右，这与全球Rodinia超大陆裂解事件一致。扬子地块周缘和华夏地块东部发育大量新元古代中期830~750 Ma的岩浆岩和火山-沉积盆地，岩浆岩以大规模的花岗岩和酸性火山岩为主，其次为玄武岩和基性侵入体[11, 64-69]。对扬子地块周缘裂谷盆地及其中岩浆岩地质特征分析表明，华南与Rodinia超大陆关系密切，新元古代中期，华南位于Rodinia超大陆裂解重要位置[11, 70-72]。在地幔柱作用下，华南与Rodinia超大陆同步裂解，Rodinia的聚合和裂解决定了华南新元古代晚期和早古生代的洋陆格局与构造演化。

在谐和性较好的数据中包含了相当数量的新太古代晚期—古元古代早期(2600~2100 Ma)信息，与全球范围内新太古代晚期岩浆活动和高级变质时代一致。对比近年来华夏地块大量新太古代岩浆活动和高级变质作用事件[46, 57, 73, 74]推测新太古代可能是华夏地块前寒武纪地壳物质形成期之一，本次测试捕捉到这个信息，对研究华夏地块基底形成演化有借鉴价值。

此外，本次测试还获得了9组大于2800 Ma且谐和性较好的数据，其中4组大于3000 Ma，最老的年龄为3602 Ma，这是湘南—桂东北地区至今发现的最古老的年龄信息。在前人的研究中也普遍发现了太古宙碎屑锆石的存在。如在研究区东侧华夏和扬子地块碰撞接合带东段，广东南部增城地区，北部檀溪地区和四堡造山带内均存在大于3000 Ma的碎屑锆石[75, 76]；在研究区西南部钾镁煌斑岩捕掳晶锆石和潭溪片麻岩中也有3000 Ma的年龄信息记录[73, 77]。由于在华夏地块至今没有真正的太古宙结晶基底的报道，对于这些太古宙碎屑锆石现在主要有两种观点：一种是以Li et al. (2014)为代表的，认为这些太古宙碎屑锆石来自其他曾经与华夏地块相邻的外来地块[13]；另一种是以张国伟等(2013)为代表的，认为华南大陆存在分布较广的太古宙结晶基底，同时还有冥古宙物质信息，这些太古宙碎屑锆石来自华夏陆块本身未初露/未厘定的太古宙结晶基底[72]。本次在湘南—桂东北地区太古代碎屑锆石的发现，有助于研究华夏地块太古代演化历史，但是对于这部分锆石的具体来源，还有待进一步的研究。

4.2 沉积物源区分析

本次将研究区样品碎屑锆石年龄频率直方图与扬子地块和华夏地以及邻区湘南、湘东南地区碎屑锆石年龄频率直方图做对比(图5)，希望可以识别沉积物的来源。

CL图像中(图3)，样品中碎屑锆石普遍具有一定程度的磨圆，年龄较大的锆石，特别是太古宙锆石，古元古代锆石磨圆程度较高，反映经历了较远距离的搬运作用。但是，在样品薄片显微照片中，4件样品中碎屑矿物(石英)的磨圆度和分选性均较差，多位棱角-次棱角状，反映物质搬运距离较近，为近源沉积。综合分析认为，研究区寒武纪—奥陶纪地层中碎屑锆石特别是年龄较老的锆石经历了二次或多次搬运作用，由其最初的物源区经过一次或多次的搬运作用沉积在研究区附近，再经过最后一次近距离的剥蚀搬运作用在现今的地方沉积下

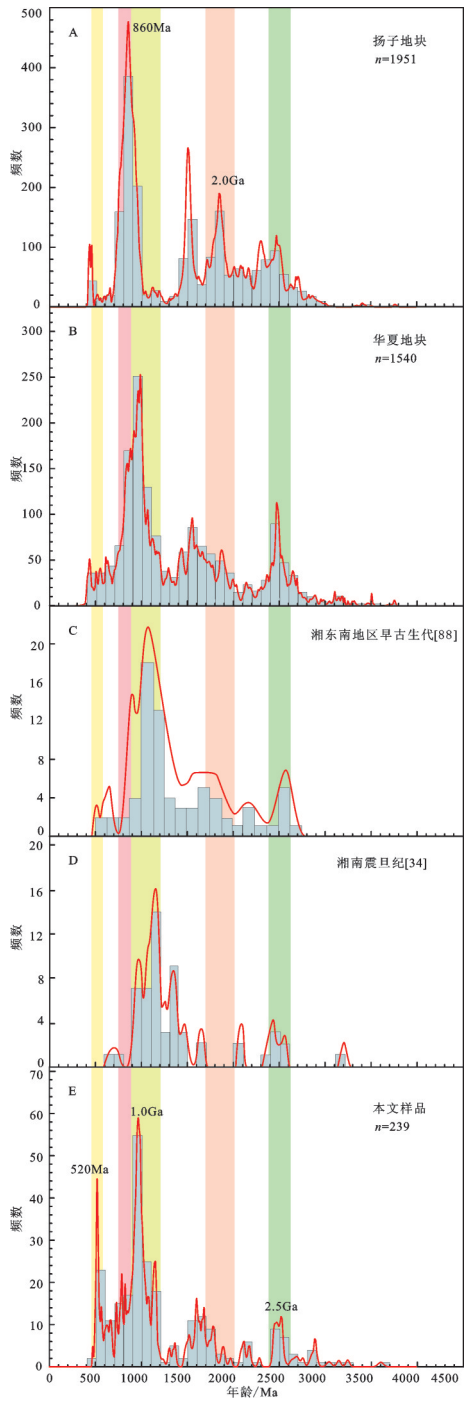

图5 A-扬子地块南部碎屑锆石统计年龄频率直方图(数据来自文献[34, 79-83]);B-华夏地块碎屑锆石统计年龄频率直方图(数据来自文献[46, 56, 57, 75, 76, 84-87]);C-湘东南地区早古生代碎屑锆石年龄频率直方图(数据来自文献[88]);D-湘南震旦纪地层碎屑锆石年龄频率直方图(数据来自文献[34]);E-本文研究区(湘南桂东北地区)碎屑锆石统计年龄频率直方图

Fig.5 A-Detrital zircon age frequency histogram of South Yangtze Block (data after references [34, 79-83]); B-Detrital zircon age frequency histogram of Cathaysia Block (data after references [46, 56, 57, 75, 76, 84-87]); C-Detrital zircon age frequency histogram of Early Paleozoic in south Hunan Province (data after reference [88]); D-Detrital zircon age frequency histogram of Sinian in southern Hunan Province (data after reference [34]); E-Detrital zircon age frequency histogram of this study

来。其中2.5 Ga左右的碎屑锆石可能来自华夏地块与扬子地块未出露太古宙基底物质,也不排除来自曾经与华夏地块相邻的具有太古宙结晶基底大陆的可能;1.77 Ga左右的碎屑锆石可能来自扬子地块或华夏地块自身或劳伦古陆,澳大利亚和东南极这些曾经与华夏地块相邻的古陆;而1.0~0.75 Ga的碎屑锆石可能来自华夏地块或扬子地块或同时来自两个地块同期的花岗岩[13, 14]。

由于华夏地块和扬子地块具有不同的前寒武纪演化历史,在新元古代之前,它们并不是统一的大陆,其岩石组成,时代组合,地球化学以及后期地质演化等,存在明显差异,华夏地块和扬子地块前寒武纪锆石年龄具有不同的分布特征。对华夏地块粤中、赣南、广西东部、湘中、湘东、湘东南、湘桂交界等地区[14, 34, 35, 46, 55-57]新元古代到中生代沉积岩研究表明,华夏地块以包含大量Grenville期(1.0 Ga左右)和新太古代(2.5 Ga左右)碎屑锆石为特征。而扬子地块则以大量Rodinia裂解期(860~780 Ma)岩浆事件为标志,这期事件在华夏地块反映不明显,仅限于华夏东部的北武夷地区,同时,扬子地块发育2.0 Ga左右的岩浆活动,而华夏地块却未发现这些事件记录,故年龄谱上860~780 Ma和2.0 Ga处形成的峰也可以作为扬子地块特征。扬子地块虽然也有1.0 Ga左右锆石报道,但主要位于扬子地块西缘,离研究区较远,且在扬子地块西缘的岩浆活动中也不占主导地位。

本次研究碎屑锆石存在800 Ma、970 Ma、1100 Ma、1650 Ma、2500 Ma等年龄峰,华夏地块和扬子地块碎屑锆石特征峰在本次研究中均有体现,说明研究区寒武纪—奥陶纪地层可能接受来自两地块物质沉积。

华南在Rodinia期裂解形成南华裂谷系后,经晚

寒武世—早奥陶世的郁南运动,云开地块由南向北运动与桂滇—北越地块发生碰撞(图1-B),造成了云开地区褶皱隆升和由南向北的推覆构造[78],在研究湘东南泗洲山地区南华系和震旦系地层时得出古水流方向为南东至北西向[35],证明沉积物主要由华夏地块提供。古地理方面,研究区位于荔浦断裂南东侧桂东凹陷,寒武纪时期桂东地区位于扬子古地理体系和华夏古地理体系之间,物源主要来自华夏古陆,少量来自扬子地块西南的滇中古陆和牛首山岛[33]。此外,王鹏鸣等在研究湘东南地区南华纪和震旦纪沉积岩时,也认为物源主要来自华夏地块[34, 35]。结合前人资料认为,湘南—桂东北地区寒武纪—奥陶纪地层物源主要来自华夏地块,少量来自扬子地块,研究区与华夏地块亲缘性更高。

4.3 华夏地块与扬子地块西南段边界初步探讨

对于华夏地块和扬子地块西南段界线问题,学术界存在较多观点。殷鸿福等(1999)从多岛洋体系出发,认为华夏与扬子南段界线应该以云开地块的北界为界线,即钦州—岑溪—罗定—云浮构造混杂岩带[25];Xu et al. (2007)从地层学方面分析,认为扬子地块与华夏地块的分界线应以在华南板块出露的板溪群的南部边缘为界[89];张国伟等(2002)和Guo et al. (2009)对滇东南火山岩和花岗岩的研究,认为滇东南—黔西南的弥勒—师宗—罗平—兴义—望谟—罗甸一线为扬子地块与华夏地块的碰撞带[27,28];杨明桂等(2009)认为扬子地块和华夏地块晋宁期西南段结合带位于萍乡—衡阳东—北海一线[29];Zhang and Wang (2007)通过对华南地区地壳地震波分析,认为华夏地块和扬子地块西南段边界断裂应为吴川—四会断裂[90];饶家荣等(2012)通过研究深部地球物理资料,认为扬子地块和华夏地块深部结合带北西边界大致在安徽歙县—南昌—湖南大围山—沩山—城步—广西河池一线,南东边界大致在江山—绍兴—新余—萍乡—衡东—双牌—桂林—柳州一线,在湖南位于钦杭结合带[30];付建民等(2004)认为茶陵—郴州断裂为华夏地块与扬子地块在湖南段的界线[26];张建新等(2000)和Wang Y et al. (2010)通过分析郴州—临武断裂两侧地球化学特征以及岩体特征,认为郴州—临武断裂为华夏地块和扬子地块西南段边界断裂[18,31];陈懋弘等(2006)通过解析桂北—桂东地区古地理特征,提出以荔浦断裂作为扬子地块与华夏地块西南端界线断裂[33];王鹏鸣等(2012,2013)认为扬子地块和华夏地块西南地区的分界线位于苗儿山与金鸡岭之间[34, 35],等等。本次研究区位于上述几种观点重合部位,结合沉积岩物源分析,本文认为研究区位于华夏地块与扬子地块碰撞结合带内,但具体界线位置还有待进一步研究。

5 结 论

(1)本文通过对湘南—桂东北地区寒武纪和奥陶纪地层碎屑锆石年代学研究,获得了丰富的年龄信息,有效U-Pb年龄值位于3146~474 Ma,主要集中分布于2633~2473 Ma、1880~1521 Ma、1146~911 Ma、896~720 Ma、536~474 Ma这5个时间段,反映物源区古太古代到奥陶纪经历了多期构造-岩浆事件。

(2)大量970 Ma左右和800 Ma左右的年龄表明全球Grenville造山事件和Rodinia超大陆裂解事件对华南影响显著,大量泛非期(520 Ma左右)年龄,表明华夏地块可能与冈瓦纳关系密切。

(3)研究区与扬子地块和华夏地块都具有亲缘性,研究区地层同时接受华夏地块和扬子地块物质沉积,物源大部分来自华夏地块,少部分来自扬子地块,结合前人资料,认为研究区应位于华夏地块和扬子地块碰撞拼合带内。

致谢:匿名审稿人提出的建设性意见对本文的修改提供了重要帮助,编辑部李亚萍老师在本文修改中提出许多宝贵的意见,在此一并表示衷心的感谢!

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