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黔东北沿河县奥陶系湄潭组碎屑锆石特征、物源 ——构造意义及其成矿年代学启示

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摘要:黔东北沿河县位于中扬子地区,分布有众多低温热液矿床,构造上位于加里东期前陆盆地的隆后带,是研究盆地物源–构造响应的良好场所,然而在中扬子的大部分地区,奥陶纪地层序列多以碳酸盐岩为主夹泥质岩,因而从岩性上制约了碎屑锆石年代学等定量分析手段的开展。近来,笔者注意到沿河县及周边地区下一中奥陶统湄潭组(O₂-m)为泥岩、灰岩夹(钙质)砂岩,采样分析结果表明,湄潭组碎屑锆石年龄大于1.0 Ga的锆石仅8颗(占12%)且未形成峰值,最年轻一组谱和年龄的加权平均值((457.8±8.1)Ma)与该组沉积上限十分接近,反映湄潭组碎屑主要来自新隆升的物源区,且具有相对较高的沉积速率。根据年龄的分布和特征峰值,可分为5组:~461 Ma(I)、~580 Ma和~606 Ma(II)、~722 Ma(III)、~865 Ma(IV₁)和~936 Ma(IV₂),其中Eu正异常的锆石集中分布于第I组(占62%),而在第II组和第IV₂组中缺失,结合稀土元素等的分析,认为其物源主要分为3部分,第I组、第II组和第IV₂组、第III和IV₁组,分别主要来自3个不同的物源区,分别对应黔中隆起、扬子西缘康滇古陆(另有少量来自扬子东南缘—华夏地区)、武陵—雪峰隆起。此外,第I组年龄450~511 Ma范围内发育了高达73%的热液锆石,与区域低温热液成矿时间对应,认为其形成是物源区流体的活跃导致的,可能与奥陶纪区域构造体制从伸展到挤压的转换有关,暗示此时加里东运动已经开始波及中扬子沿河地区,但主要表现为热液活动,并没有发生大规模岩浆作用。

关键词:奥陶纪;湄潭组;碎屑锆石;物源;热液锆石;中扬子;低温热液矿床;矿产勘查工程

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Detrital zircons of the Meitan Formation during Ordovician in Northeastern Guizhou and its significance for provenance–tectonic and implications for metallogenic chronology

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Abstract: Located in northeastern Guizhou of middle Yangtze area, Yanhe County has many low-temperature hydrothermal deposits. It is a good place for studying the provenance-tectonic response of the basin due to its back-bulge position during Ordovician. However, in most area of middle Yangtze, stratigraphic sequence is composed mainly of carbonate rocks intercalated with mudstone, which restricts the development of quantitative analytical methods such as the detrital zircon geochronology. Recently, the authors noticed that there are mudstone and carbonate intercalated with sandstone around Yanhe in the Meitan Formation (O₁₋₂m) of lower-middle Ordovician. A detrital zircon sample from the sandstone shows that only 8 zircons (12%) are older than 1.0Ga and they have no age peaks, and the weighted average of the youngest group of zircons ((457.8 ± 8.1) Ma) is close to the upper limit of the Meitan Formation. This means that the detritus of the Meitan Formation was mainly derived from a newly formed source area and had a relatively high deposition rate. The age of zircons can be divided into five groups according to their age distribution and peaks: ~461 Ma (I), ~580 Ma and ~606 Ma (II), ~722 Ma (III), ~865 Ma (IV₁) and ~936 Ma (IV₂). On the basis of isotope ratio and REE, the authors consider that the ages can be divided into three parts: I, II and IV₂, III and IV₁, which are mainly derived from three different source areas. Combined with the previous study, the authors hold that the three source areas are Qianzhong uplift, Kangdian ancient land, and Wuling-Xuefeng uplift, with Qianzhong and Kangdian being newly formed source area. What's more, there are many (73%) hydrothermal zircons in age group I (450~511 Ma), and this age matches well with low-temperature hydrothermal mineralization, suggesting that it was caused by the activation of the fluid, probably due to the regional tectonic regime converted from extension to compression. This implies that the Caledonian movement had begun to affect the Yanhe area, but was mainly manifested as hydrothermal activity, with no large scale of magmatism.

Key words: Ordovician; Meitan Formation; detrital zircon; provenance; hydrothermal zircon; middle Yangtze; low-temperature hydrothermal deposit; mineral exploration engineering

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1 引 言

黔东南沿河县位于中扬子地区,构造上位于加里东期前陆盆地的隆后带(尹福光等,2001),是研究盆地物源-构造响应的良好场所,然而,在中扬子的大部分地区,奥陶纪地层序列多以碳酸盐岩为主夹泥质岩,因此以往研究通常更为关注地层古生物、岩相古地理等方面(陈朋飞和詹仁斌,2006;谢尚克等,2011),而对其作为隆后盆地的物源响应不甚明晰。另外,沿河及其周边地区分布有众多低温热液矿床,其成矿与地层关系密切(李堃等,2013;

张遵遵等,2018a),以往认为其成矿作用应发生在燕山期(侯兵德等,2011;张建忠等,2014),而近年来,随着同位素定年技术的进步,部分学者相继获得了加里东期的成矿时代(段其发等,2014;杨红梅等,2015;张遵遵等,2018b),这与同期的构造运动及盆地演化是否具有耦合关系,还有待更多证据的发掘。

锆石的物理化学性质稳定、抗风化能力强,是沉积岩中常见的副矿物之一,其U-Pb同位素定年手段非常成熟,因而在限定地层时代(Pi and Jiang, 2016)、示踪物源(宋芳等,2016)、分析古地理和构造演化(Yao et al., 2015)等方面均得到了广泛应

用。另一方面,在有流体存在的情况下,中—低级变质作用也可引起锆石结构、组成和年龄发生变化 (Bomparola et al., 2007; Geisler et al., 2007),从而形成热液锆石(毕诗健等,2008;万渝生等,2011),这在限定热液矿床的成矿年龄方面应用较为广泛,尤其是石英脉型金矿床(Wang et al.,2018)。虽然锆石分析方法有诸多优点,但对于一些以非碎屑岩为主的地层或碎屑岩粒度非常细的时候,锆石分析的应用就会受到限制。中扬子地区的奥陶系即是典型的扬子型碳酸盐岩台地沉积,总体岩性上并不适合开展定量的碎屑锆石年代学分析,且含有丰富的古生物化石,加之该地奥陶系出露广、露头好、沉积连续,盆地古地理和沉积背景研究成果(黄福喜等,2011;谢尚克等,2011;李皎等,2015;黄乐清等,2018)已经十分丰富,因此,关于该地碎屑锆石的研究较少见到。笔者在重庆宜居—贵州沿河一带开展1:5万矿产地质调查过程中注意到,该地区的中奥陶统湄潭组在部分剖面夹含砂岩或钙质砂岩,因

而选取沿河地区的湄潭组有针对性地开展了碎屑锆石研究,对其年龄分布、物源、微量元素等进行综合分析,最大限度地挖掘其中蕴含的地质意义,以期对物源状况、构造古地理格局、成矿年代学等方面的进一步研究有所启发。

2 地质背景及采样测试

黔东北沿河地区位于扬子地块中部,江南造山带北西一侧,早古生代地层十分发育(图1),其中奥陶系自下而上划分为桐梓组、红花园组、湄潭组、十字铺组、宝塔组、临湘组、五峰组,总体地层序列上可与峡东宜昌地区很好地对比(图2),较为特别的是,这里的湄潭组与大湾组不同,后者为一套含泥质较高的碳酸盐岩地层,而前者在一些剖面上发育含钙的砂岩,并且可见笔石化石。前人研究认为沿河地区湄潭组的岩性特征介于典型湄潭组和典型大湾组之间,具有过渡色彩(陈朋飞和詹仁斌,2006)。考虑到这套砂岩在判断物源方面的特殊意

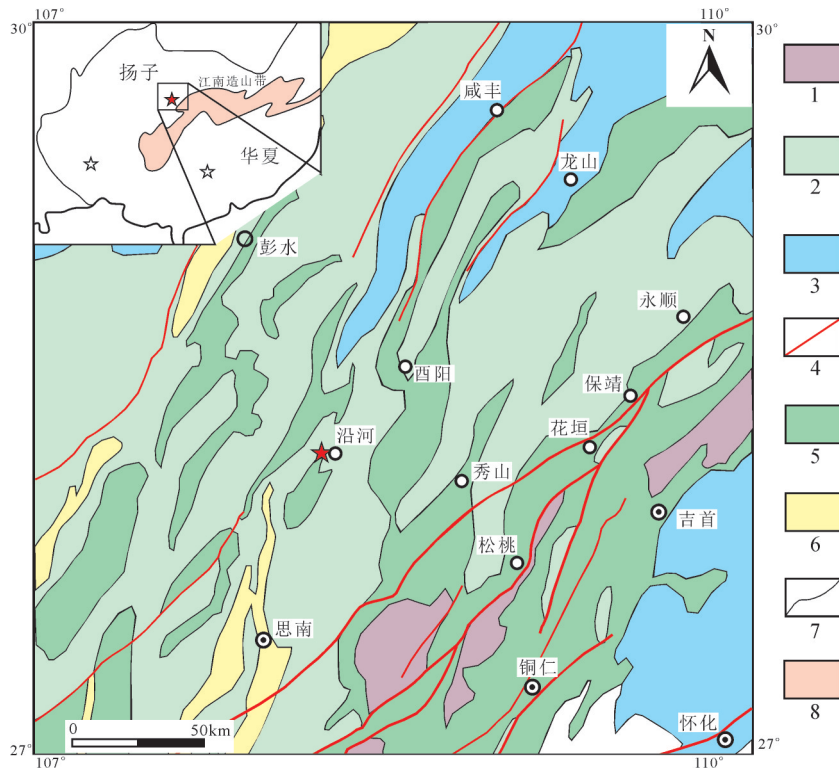


图1 研究区地质简图(据张遵遵等,2018b修改,红色星号为本文采样位置,白色星号为前人样品点)

1—新元古界;2—奥陶—志留系;3—中生界;4—断裂;5—寒武系;6—上古生界;7—地质界线;8—江南造山带

Fig. 1 Sketch geological map of the study area (modified from Zhang Zunzun et al., 2018b, red star shows sample location, white stars show cited sample location)

1—Neoproterozoic; 2—Ordovician-Silurian; 3—Mesozoic; 4—Fault; 5—Cambrian; 6—Upper Paleozoic; 7—Geological boundary; 8—Jiangnan Orogen

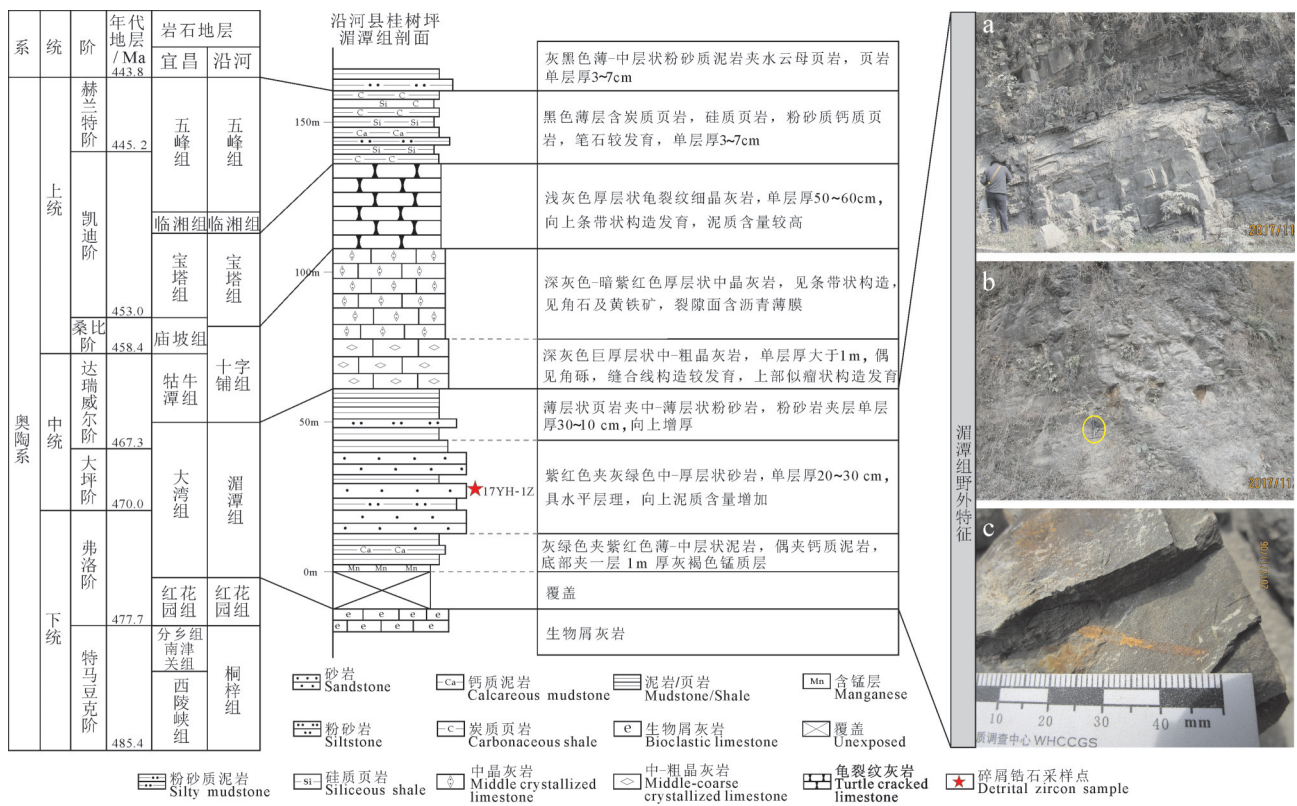


图2 实测岩石地层序列及采样层位(地层对比据汪啸风,2016;年代地层据樊隽轩等,2018)

a—湄潭组宏观露头;b—本文锆石采样处;c—湄潭组含钙细砂岩中的笔石化石

Fig.2 Measured stratigraphic sequence and sampling position (chronostratigraphic and stratigraphic correlation after Wang Xiaofeng, 2016 and Fan Junxuan et al., 2018)

a—Outcrops of the Meitan Formation;b—Sampling place of this paper;c—Graptolite in calcium-bearing fine sandstone of the Meitan Formation

义,因而本次工作在沿河县山坪村桂树坪公路边出露的湄潭组黄绿色含钙细砂岩中,采集碎屑锆石样品1件,样品位置见图2,采样坐标为28°33'11.1"N;108°28'48.0"E。

样品的锆石挑选、制靶、透反射及阴极发光(CL)照相均在南京宏创地质勘查技术服务有限公司完成。岩石样品破碎后采用比重法淘选,然后在双目镜下进行人工挑纯;再将挑选出来的锆石用环氧树脂进行固定,经抛光后分别进行照相。锆石U-Pb同位素测年在武汉上谱分析科技有限责任公司利用激光剥蚀电感耦合等离子质谱仪(LA-ICP-MS)完成。随机选择不同色泽、形态、粒径的锆石进行测试,以图像显示的锆石形态和内部特征作为锆石U-Pb原位分析测点的依据,避开包体和裂缝等不利部位。测试过程中使用的束斑直径为32 μm。实验数据采用ICPMSDataCal 11.5软件处理,具体流程参考Liu等(2010a,2010b)的论文,处理得到的数据经ComPbCorr#3.12(Anderson,2002)进行铅校

正后,再用Isoplot 3.7(Ludwig,2001)成图。

3 测试结果

样品17YH-1Z中碎屑锆石颗粒大多呈次圆状、粒状,少量长柱状,大小40~100 μm不等。部分锆石阴极发光图像(CL)如图3所示,多数锆石具有震荡环带,且Th/U比值大于0.4,显示为岩浆成因,但也有相当一部分锆石CL图像较深,环带不明显或受到后期破坏,表现出变质锆石的特征。

对该样品进行了80颗锆石分析,获得谐和度大于90的数据共66个(表1),对于年龄大于1000 Ma的测点采用²⁰⁷Pb/²⁰⁶Pb年龄,而对于小于1000 Ma的测点则采用²⁰⁶Pb/²³⁸U年龄。结果表明,这66个数据中的大部分测点年龄分布在450~984 Ma(占88%),只有一颗锆石出现了(386 ± 5)Ma的谐和年龄,造成该点年龄偏离的原因尚不清楚,可能不具备明确的地质含义(暂视为小概率事件,离群年龄),除此之外最年轻的1组锆石加权平均年龄为(457.8 ±

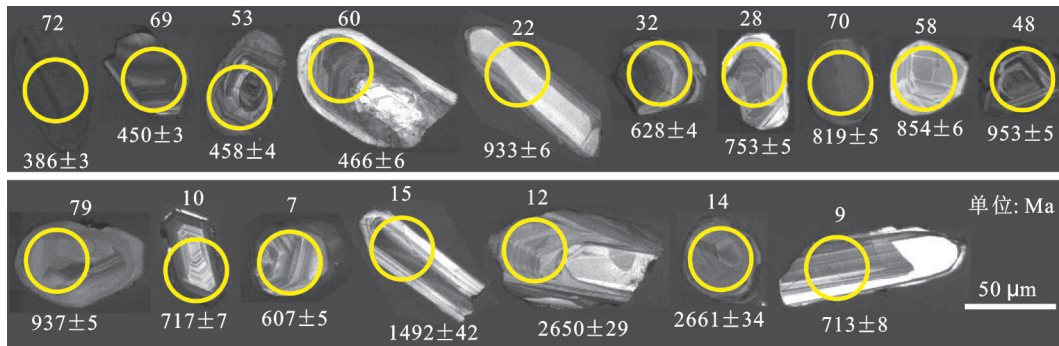


图3 碎屑锆石代表性阴极发光(CL)图像、测点位置及年龄(Ma)
Fig.3 Representative CL images and dating spots of the detrital zircon grains

8.1)Ma(MSDW = 2.9, $n = 5$)(图5c),与生物地层研究得出的湄潭组沉积上限(468~458 Ma)十分接近,反映湄潭组沉积速率较高或者可能是湄潭组在接受其碎屑沉积的同时,物源区也在遭受变质作用和隆升剥蚀。对测点年龄进行排序发现,锆石年龄主要分布在4个年龄比较连续的区域,据此将其分为4组:450~511 Ma(I)、555~649 Ma(II)、695~773 Ma(III)、810~984 Ma(IV),另有分布于1144~2650 Ma的锆石,由于在长达1.5 Ga的时间段内仅出现8颗(占12%)且未形成峰值(图4c),这里暂不予讨论。

为方便下文对比,图4a列出了潜在物源区前寒武纪碎屑锆石年龄谱特征(扬子西缘、华夏曲线引自李献华等,2012;江南造山带曲线引自Geng, 2015);图4b和4d为邻近地区湄潭组相当层位的碎屑锆石年龄谱(数据分别引自张雄等,2016;韩志锐等,2017)。

4 讨论

4.1 物源分析

概率密度曲线显示(图4e),上述4组年龄对应的年龄峰值分别为:461 Ma(I)、580 Ma(II₁)和606 Ma(II₂)、722 Ma(III)、865 Ma(IV₁)和936 Ma(IV₂)。根据已有研究(Li et al., 2003;陆松年,2004;夏林圻等,2009;高林志等,2011;陈建书等,2016;崔晓庄等,2016;王孝磊等,2017;徐亚军等,2018),这些峰值分别对应加里东运动(400~520 Ma)、泛非运动(550~600 Ma)、新元古代裂谷活动(725~820 Ma)、晋宁运动(820~860 Ma)、Grenville期岩浆活动(900~1200 Ma),其中第IV组由于包含了两期构造-岩浆活动的年龄峰值,故可以两者峰值为代表再细

分为IV₁和IV₂两个组。因此,说明湄潭组碎屑中主要包含了以上5个物源组分。并且,由于年龄大于1000 Ma的锆石占比非常少,说明湄潭组砂岩中的碎屑可能主要来源于新隆升的物源区,因为随着剥蚀的加深,成熟物源区会剥露出更高比例的基底碎屑,从而出现较高比例的古老基底锆石。

对样品中所有数据点做谐和图(图5a),可以看出这些数据点大多不同程度地偏离了谐和曲线,说明这些锆石多数遭受了铅丢失。通常而言,可通过不一致线对放射成因铅丢失引起的年龄偏离进行校正,上交点对应锆石形成年龄,而下交点则对应锆石的变质年龄(张永清等,2015),虽然对于碎屑锆石而言,这些上下交点的地质意义有限,但是如果其中大多数锆石都是由单一事件引发时,仍然可以拟合出一条不一致线,经过辨别也可以从中发现一些有用的信息。从这4组数据的铅丢失程度看,大致有两种趋势:第I、II、IV组锆石的铅丢失相对轻微,大致可构成一条较“陡”的不一致线;第III组锆石铅丢失相对较多,大致构成一条较“缓”的不一致线。暗示湄潭组的物源可能分为两部分或来源于同一物源区的不同变质部位。

为了更直接地辨别这两部分物源,笔者尝试进一步对第I、II、IV组年龄生成谐和曲线和不一致线,得出其上下交点分别为(1113 ± 53)Ma和(443 ± 54)Ma(MSDW = 6.2, $n=48$);对第III组年龄和年龄最老的两颗锆石年龄做谐和曲线和不一致线,得出其上下交点分别为(2758 ± 44)Ma和(679 ± 26)Ma(MSDW = 12, $n=16$)。这些年龄与上述提及的构造-岩浆活动的年龄区间有很好的对应关系,可能表明各组年龄中均包含了部分变质物源。当然,对

表1 沿河湄潭组碎屑锆石U-Pb定年及同位素数据

Table 1 Isotope composition and age of detrital zircons from the Meitan Formation in Yanhe County

测点号	同位素比值						年龄/Ma						谐和度	Th/U
	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ		
17YH-1Z-01	0.0604	0.0011	0.8258	0.0157	0.0985	0.0010	617	41	611	9	605	6	99%	0.75
17YH-1Z-02	0.0641	0.0014	1.0130	0.0206	0.1138	0.0012	746	45	710	10	695	7	97%	0.30
17YH-1Z-03	0.0649	0.0016	0.9531	0.0222	0.1059	0.0009	772	58	680	12	649	5	95%	0.30
17YH-1Z-04	0.0612	0.0013	0.8134	0.0168	0.0957	0.0007	656	42	604	9	589	4	97%	0.47
17YH-1Z-05	0.0588	0.0012	0.7603	0.0145	0.0932	0.0007	561	47	574	8	574	4	99%	0.01
17YH-1Z-06	0.0980	0.0021	2.0730	0.0466	0.1524	0.0012	1587	41	1140	15	914	7	78%	0.50
17YH-1Z-07	0.0609	0.0015	0.8321	0.0202	0.0987	0.0008	635	52	615	11	607	5	98%	0.46
17YH-1Z-08	0.0677	0.0014	1.0950	0.0228	0.1169	0.0011	861	43	751	11	713	6	94%	0.24
17YH-1Z-09	0.0847	0.0023	1.4247	0.0422	0.1213	0.0014	1309	54	899	18	738	8	80%	1.17
17YH-1Z-10	0.0704	0.0017	1.1443	0.0289	0.1177	0.0012	939	50	775	14	717	7	92%	1.01
17YH-1Z-11	0.0798	0.0015	1.7131	0.0340	0.1547	0.0011	1192	38	1013	13	927	6	91%	0.52
17YH-1Z-12	0.1797	0.0032	10.5766	0.1848	0.4244	0.0028	2650	29	2487	16	2280	13	91%	0.87
17YH-1Z-13	0.1241	0.0147	2.7521	0.3452	0.1575	0.0012	2017	211	1343	93	943	7	65%	0.52
17YH-1Z-14	0.1808	0.0037	10.1293	0.2077	0.4030	0.0025	2661	34	2447	19	2183	12	88%	0.12
17YH-1Z-15	0.0932	0.0023	2.3632	0.0574	0.1827	0.0015	1492	42	1232	17	1082	8	87%	1.04
17YH-1Z-16	0.0559	0.0013	0.5728	0.0145	0.0736	0.0007	450	54	460	9	458	4	99%	0.24
17YH-1Z-17	0.0865	0.0017	2.0866	0.0398	0.1738	0.0011	1350	33	1144	13	1033	6	89%	0.17
17YH-1Z-18	0.0781	0.0022	1.3596	0.0366	0.1260	0.0011	1150	56	872	16	765	6	86%	0.52
17YH-1Z-19	0.0653	0.0011	0.8138	0.0148	0.0898	0.0008	783	37	605	8	555	5	91%	0.03
17YH-1Z-20	0.0695	0.0014	1.0175	0.0197	0.1056	0.0007	922	41	713	10	647	4	90%	0.21
17YH-1Z-21	0.0591	0.0009	0.6451	0.0105	0.0789	0.0006	569	6	505	6	490	4	96%	0.07
17YH-1Z-22	0.0756	0.0013	1.6188	0.0254	0.1557	0.0011	1083	35	978	10	933	6	95%	1.27
17YH-1Z-23	0.0717	0.0010	1.6338	0.0229	0.1650	0.0011	976	27	983	9	984	6	99%	0.09
17YH-1Z-24	0.0718	0.0012	1.5499	0.0250	0.1565	0.0010	981	34	950	10	937	6	98%	0.71
17YH-1Z-25	0.0714	0.0011	1.4281	0.0238	0.1447	0.0010	969	31	901	10	871	6	96%	0.69
17YH-1Z-26	0.0752	0.0016	1.4629	0.0306	0.1421	0.0017	1072	42	915	13	856	10	93%	0.84
17YH-1Z-27	0.0686	0.0011	0.6391	0.0130	0.0673	0.0008	887	32	502	8	420	5	82%	0.31
17YH-1Z-28	0.0743	0.0016	1.2688	0.0267	0.1240	0.0009	1050	43	832	12	753	5	90%	1.97
17YH-1Z-29	0.0640	0.0010	0.8768	0.0139	0.0992	0.0008	743	31	639	8	610	5	95%	0.21
17YH-1Z-30	0.0775	0.0011	1.9365	0.0377	0.1807	0.0025	1144	30	1094	13	1071	13	97%	0.41
17YH-1Z-31	0.0746	0.0011	1.6761	0.0240	0.1626	0.0009	1057	30	999	9	971	5	97%	0.64
17YH-1Z-32	0.0630	0.0011	0.8913	0.0152	0.1024	0.0007	709	35	647	8	628	4	97%	0.38
17YH-1Z-33	0.1110	0.0019	4.4453	0.0745	0.2903	0.0023	1817	31	1721	14	1643	12	95%	0.45
17YH-1Z-34	0.0600	0.0010	0.8005	0.0137	0.0965	0.0007	611	37	597	8	594	4	99%	0.09
17YH-1Z-35	0.0753	0.0010	1.4992	0.0203	0.1436	0.0009	1077	26	930	8	865	5	92%	0.63
17YH-1Z-36	0.0724	0.0017	1.2281	0.0278	0.1226	0.0008	998	53	813	13	746	5	91%	0.66
17YH-1Z-37	0.0764	0.0012	1.6137	0.0254	0.1526	0.0011	1106	32	976	10	916	6	93%	0.81
17YH-1Z-38	0.0706	0.0014	1.0124	0.0184	0.1037	0.0007	946	40	710	9	636	4	89%	0.48
17YH-1Z-39	0.0707	0.0017	1.1786	0.0288	0.1201	0.0010	950	50	791	13	731	5	92%	1.30
17YH-1Z-40	0.0706	0.0012	1.4686	0.0241	0.1503	0.0012	946	29	918	10	902	7	98%	0.28
17YH-1Z-41	0.0900	0.0014	2.7366	0.0473	0.2193	0.0019	1425	30	1338	13	1278	10	95%	1.44
17YH-1Z-42	0.0733	0.0017	1.5270	0.0349	0.1510	0.0015	1033	79	941	14	907	8	96%	1.65

续表1

测点号	同位素比值						年龄/Ma						谐和度	Th/U
	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		
17YH-1Z-43	0.0901	0.0046	2.2791	0.1199	0.1846	0.0029	1428	99	1206	37	1092	16	90%	0.03
17YH-1Z-44	0.0688	0.0015	1.1766	0.0260	0.1237	0.0010	892	42	790	12	752	6	95%	0.29
17YH-1Z-45	0.0717	0.0018	1.4142	0.0336	0.1430	0.0012	989	51	895	14	862	7	96%	1.44
17YH-1Z-46	0.1139	0.0019	5.1035	0.0839	0.3236	0.0021	1863	31	1837	14	1807	10	98%	1.04
17YH-1Z-47	0.0883	0.0018	1.5401	0.0359	0.1250	0.0010	1391	39	947	14	760	6	78%	0.91
17YH-1Z-48	0.0721	0.0010	1.5928	0.0232	0.1593	0.0009	989	30	967	9	953	5	98%	0.78
17YH-1Z-49	0.0707	0.0013	1.4699	0.0272	0.1502	0.0010	947	38	918	11	902	5	98%	1.21
17YH-1Z-50	0.0731	0.0013	1.4031	0.0376	0.1369	0.0024	1017	35	890	16	827	14	92%	0.41
17YH-1Z-51	0.0658	0.0012	0.8772	0.0180	0.0962	0.0011	798	37	639	10	592	7	92%	0.75
17YH-1Z-52	0.0605	0.0010	0.6854	0.0123	0.0815	0.0006	633	35	530	7	505	3	95%	0.17
17YH-1Z-53	0.0588	0.0013	0.5996	0.0135	0.0737	0.0007	561	44	477	9	458	4	96%	1.43
17YH-1Z-54	0.0599	0.0011	0.6210	0.0114	0.0747	0.0005	611	39	490	7	464	3	94%	0.41
17YH-1Z-55	0.0839	0.0015	1.6982	0.0305	0.1462	0.0009	1300	35	1008	12	879	5	86%	0.55
17YH-1Z-56	0.0599	0.0013	0.7834	0.0165	0.0943	0.0006	611	51	587	9	581	4	98%	0.37
17YH-1Z-57	0.0660	0.0015	1.0846	0.0238	0.1186	0.0007	806	42	746	12	723	4	96%	0.45
17YH-1Z-58	0.0737	0.0017	1.4432	0.0335	0.1416	0.0011	1035	47	907	14	854	6	93%	0.31
17YH-1Z-59	0.0618	0.0011	0.6336	0.0130	0.0742	0.0011	733	37	498	8	461	6	92%	0.54
17YH-1Z-60	0.0730	0.0015	0.7729	0.0234	0.0750	0.0011	1013	41	581	13	466	6	78%	0.43
17YH-1Z-61	0.0671	0.0010	1.1034	0.0169	0.1186	0.0008	843	30	755	8	723	5	95%	0.03
17YH-1Z-62	0.0698	0.0014	1.2299	0.0235	0.1274	0.0008	924	41	814	11	773	5	94%	0.23
17YH-1Z-63	0.0738	0.0018	1.5221	0.0388	0.1491	0.0015	1035	50	939	16	896	8	95%	0.52
17YH-1Z-64	0.0656	0.0021	0.8220	0.0255	0.0911	0.0008	794	69	609	14	562	5	91%	2.25
17YH-1Z-65	0.0716	0.0012	1.5534	0.0259	0.1569	0.0009	976	35	952	10	939	5	98%	1.72
17YH-1Z-66	0.0719	0.0014	1.4753	0.0287	0.1488	0.0013	983	45	920	12	894	7	97%	2.77
17YH-1Z-67	0.1590	0.0020	8.7022	0.1116	0.3955	0.0020	2456	21	2307	12	2148	9	92%	0.30
17YH-1Z-68	0.0666	0.0016	0.8623	0.0210	0.0939	0.0007	833	52	631	11	578	4	91%	0.82
17YH-1Z-69	0.0608	0.0011	0.6080	0.0117	0.0722	0.0005	632	41	482	7	450	3	92%	1.31
17YH-1Z-70	0.0711	0.0012	1.3312	0.0235	0.1355	0.0008	961	36	859	10	819	5	95%	0.11
17YH-1Z-71	0.0643	0.0009	0.8712	0.0140	0.0980	0.0009	754	31	636	8	603	5	94%	0.35
17YH-1Z-72	0.0584	0.0008	0.4988	0.0077	0.0617	0.0005	546	28	411	5	386	3	93%	0.23
17YH-1Z-73	0.0657	0.0025	0.7418	0.0268	0.0825	0.0009	798	78	563	16	511	5	90%	2.95
17YH-1Z-74	0.1270	0.0030	5.2335	0.1268	0.2984	0.0020	2057	42	1858	21	1683	10	90%	0.72
17YH-1Z-75	0.0000	0.0000	0.0000	0.0000	1.3087	0.0000	error	error			5394	3	Error	0.00
17YH-1Z-76	0.0740	0.0013	1.6292	0.0289	0.1594	0.0011	1043	36	982	11	953	6	97%	0.65
17YH-1Z-77	0.1068	0.0018	2.1085	0.0616	0.1402	0.0024	1746	31	1152	20	846	13	69%	0.41
17YH-1Z-78	0.0784	0.0015	1.6752	0.0314	0.1546	0.0012	1167	37	999	12	927	7	92%	0.17
17YH-1Z-79	0.0696	0.0013	1.5068	0.0276	0.1565	0.0010	917	37	933	11	937	5	99%	0.52
17YH-1Z-80	0.0731	0.0015	1.3514	0.0272	0.1339	0.0009	1017	42	868	12	810	5	93%	0.68

表2 沿河涓潭组碎屑锆石(17YH)微量元素(10⁻⁶)数据
Table 2 Trace elements of detrital zircons from the Meitan Formation in Yanhe County(10⁻⁶)

测点	P	Ti	Y	Nb	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Th	U
1	921.24	8.07	2128.20	11.24	4.75	60.99	4.61	29.72	23.40	6.39	70.08	20.98	224.03	74.24	302.03	66.16	617.46	101.13	10919.35	6.20	673.25	901.92
2	303.91	6.77	742.18	1.64	0.36	9.30	0.84	8.30	11.24	2.59	36.21	9.96	92.96	27.16	98.71	20.55	186.58	29.14	12683.54	0.91	305.08	1003.95
3	532.93	15.28	651.81	0.82	1.54	9.86	0.75	6.40	3.26	0.60	13.24	4.60	54.75	20.99	98.36	22.97	226.60	42.61	11606.86	0.52	78.93	261.75
4	206.92	3.52	406.31	2.19	0.05	22.85	0.06	0.82	1.80	0.65	9.21	2.98	34.30	12.67	58.29	14.75	156.66	32.30	14478.36	0.91	256.78	549.87
5	166.26	1.01	66.19	0.27	0.00	0.22	0.01	0.06	0.38	0.33	5.60	1.76	12.16	2.07	4.87	0.80	6.13	0.86	13828.27	0.18	4.45	695.67
6	377.92	6.60	1105.29	4.41	0.28	13.28	0.25	5.38	4.16	0.30	23.07	8.09	100.81	39.17	173.38	37.04	333.48	62.35	12858.71	2.14	136.23	269.91
7	402.03	9.92	1014.00	3.34	0.04	8.23	0.00	2.69	5.44	0.20	27.37	8.70	102.73	37.01	154.39	32.92	299.91	49.42	10400.27	1.70	140.09	302.07
8	1736.77	13.11	4037.82	3.67	5.49	20.95	4.40	27.52	25.66	19.85	95.88	35.53	417.05	141.01	605.14	141.59	1350.93	220.94	13293.05	3.19	370.39	1562.99
9	523.13	4.82	2663.03	3.09	0.11	12.56	0.31	5.87	11.76	3.07	69.22	23.16	269.79	97.24	392.45	79.74	692.23	116.95	10256.42	1.00	346.14	295.15
10	629.29	9.62	2025.93	5.02	0.47	49.10	0.45	3.83	6.33	3.05	34.72	12.81	168.44	69.20	328.31	79.50	791.15	146.95	12978.58	2.14	302.71	299.59
11	670.08	25.01	1589.22	2.94	0.02	3.19	0.21	3.71	8.56	0.26	43.43	13.96	159.76	56.03	239.46	52.74	493.51	83.81	13003.27	3.80	239.88	465.42
12	368.25	10.33	575.76	3.89	0.01	29.26	0.07	1.12	2.38	0.45	12.02	4.20	49.20	19.35	90.19	22.95	236.38	43.08	11313.00	2.01	193.95	222.19
13	321.71	11.99	415.59	1.70	0.00	3.22	0.02	0.40	0.98	0.15	6.37	2.64	34.05	13.97	65.33	15.94	163.49	28.61	12305.97	1.56	119.80	228.53
14	557.29	8.08	854.92	1.60	0.00	4.24	0.07	1.27	3.80	0.81	24.38	7.86	82.33	28.84	119.23	27.43	267.12	46.98	12717.60	1.98	78.64	629.57
15	324.98	5.18	897.31	1.05	0.06	25.00	0.26	3.76	5.88	2.57	26.42	7.35	78.95	28.61	128.48	30.62	310.57	61.06	10474.43	0.74	310.84	298.85
16	519.11	13.13	1530.14	10.09	5.63	40.96	5.22	28.68	19.22	20.57	39.41	13.10	142.10	49.46	221.51	55.05	556.88	96.67	11710.06	7.19	674.97	2857.09
17	247.09	0.46	176.00	0.34	0.00	3.73	0.00	0.06	0.21	0.20	1.64	0.79	11.00	5.26	29.50	8.92	106.02	24.58	11700.07	0.40	96.67	581.88
18	388.53	5.12	1143.98	0.46	0.00	10.14	0.11	2.07	4.62	0.68	22.73	7.57	93.60	38.05	182.45	44.29	448.97	85.88	12604.56	0.27	72.60	138.39
19	286.92	2.10	619.63	3.83	0.19	1.71	0.26	1.51	1.70	0.85	6.18	3.23	45.80	19.03	93.79	24.00	248.51	45.30	12630.59	3.25	58.69	2056.10
20	403.58	5.78	1919.46	1.80	0.01	1.57	0.09	1.95	5.03	0.42	36.46	13.27	169.77	68.25	310.98	69.47	647.89	118.79	9829.27	0.79	88.21	412.49
21	203.23	4.98	266.17	0.35	0.33	2.64	0.42	2.65	1.70	2.59	5.15	1.81	20.89	7.64	33.82	8.21	78.44	14.09	11216.18	0.05	176.37	2449.53
22	752.76	7.41	2505.09	1.54	0.14	14.54	0.74	12.31	23.99	6.24	92.32	23.93	197.78	57.48	178.07	33.07	278.10	43.84	12816.10	1.08	540.21	425.87
23	419.76	1.31	615.30	1.97	0.07	3.54	0.07	0.40	0.73	0.20	7.75	3.35	48.53	20.28	98.01	23.80	228.39	43.45	15485.18	2.51	104.65	1194.97
24	702.07	10.98	1460.83	1.86	0.08	9.42	0.22	3.06	6.34	0.64	34.87	12.25	145.32	51.49	216.04	45.34	398.42	65.22	12228.62	1.22	231.29	327.25
25	1626.33	11.76	1542.91	4.89	2.28	32.25	1.71	12.29	11.93	4.46	50.71	15.31	158.33	51.68	208.27	44.25	389.52	69.30	10760.60	2.98	573.39	833.23
26	464.94	3.99	1619.04	1.52	1.27	13.95	1.83	14.47	14.97	3.99	53.79	15.76	171.65	58.10	237.60	50.10	448.35	73.54	9344.57	0.67	214.06	254.31
27	741.60	63.62	2175.37	12.73	11.89	71.55	12.29	73.49	44.29	75.43	88.49	26.25	265.30	75.68	275.22	55.87	443.31	58.55	13440.55	21.91	1169.04	3741.77
28	922.69	4.19	2450.27	11.10	1.67	111.18	0.90	7.23	7.37	0.99	39.44	14.74	197.05	80.17	379.88	86.87	821.31	148.25	12486.61	2.45	498.10	252.61
29	2083.15	15.44	4823.74	2.94	2.89	24.73	6.36	67.17	72.92	16.99	231.89	61.57	575.45	174.74	663.69	136.27	1283.97	238.77	11474.32	1.09	220.49	1039.54
30	678.59	8.23	1201.16	1.44	0.47	8.83	0.68	5.31	8.55	2.80	49.54	18.01	162.75	38.84	114.72	20.00	154.49	21.79	15172.62	0.83	205.21	494.79
31	445.89	82.63	1612.29	4.93	0.38	37.62	0.46	4.77	6.45	1.50	29.57	10.67	135.41	55.01	264.10	62.84	625.18	117.11	11095.10	1.83	442.41	696.59
32	322.93	5.32	514.21	4.08	0.32	27.51	0.46	3.73	3.23	1.94	12.39	4.29	47.57	16.76	75.90	18.71	194.01	36.70	13113.13	1.96	237.14	632.28
33	708.55	11.80	1311.75	0.90	0.06	3.35	0.07	1.15	3.21	0.39	23.16	8.86	116.91	46.32	209.83	46.72	437.11	77.72	13403.11	0.69	75.34	168.31
34	818.45	52.82	1325.01	12.33	2.60	19.89	2.55	16.00	8.22	2.82	22.20	8.47	117.02	48.33	250.27	69.08	787.42	153.33	15027.41	23.85	77.90	893.14
35	1903.70	24.05	2432.61	12.21	3.35	77.67	3.53	25.06	22.72	20.71	74.50	21.40	221.93	74.53	344.42	90.85	1040.32	249.10	14601.26	3.47	1003.68	1595.28
36	503.20	7.53	1971.61	16.27	6.99	31.78	2.64	17.13	12.02	0.68	55.13	17.95	212.27	74.63	307.45	64.13	542.33	87.02	12083.70	5.89	136.68	207.75
37	1507.62	9.03	2386.89	2.81	6.71	26.45	3.67	23.43	17.70	2.69	65.82	23.03	260.49	86.00	333.05	65.74	537.58	82.94	12228.42	1.46	575.89	707.67
38	833.28	1.19	1556.83	4.53	2.43	16.80	1.30	8.13	5.05	0.05	21.99	9.10	125.96	52.72	258.26	63.42	614.44	107.80	15953.87	4.85	255.71	531.94
39	374.93	21.13	534.68	1.42	0.09	18.41	0.13	1.86	2.94	0.71	14.28	4.22	50.09	18.63	81.62	18.70	177.41	32.54	11189.06	0.61	156.80	120.47
40	598.62	4.13	900.70	0.91	0.01	1.43	0.06	1.02	3.72	0.58	25.27	9.11	100.22	30.06	111.02	21.88	176.03	28.43	15897.95	0.90	105.28	378.92

续表2

测点	P	Ti	Y	Nb	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Th	U
41	1445.28	14.75	2803.94	4.00	41.73	106.97	14.61	79.96	35.91	5.61	106.41	30.66	316.86	101.72	398.56	79.03	645.86	104.30	11595.77	2.12	326.27	226.34
42	798.40	5.87	866.55	1.61	19.41	40.12	3.93	18.13	7.28	0.78	26.24	7.73	87.06	30.86	126.05	25.02	218.09	37.96	13577.70	1.04	239.42	145.29
43	225.05	1.11	462.60	0.11	0.00	0.27	0.00	0.05	0.18	0.16	2.15	1.27	24.16	13.06	79.75	23.03	278.96	73.49	10758.66	0.03	0.48	18.14
44	382.78	11.94	157.29	0.54	0.01	1.27	0.07	1.66	3.83	0.21	18.30	4.07	26.46	5.13	13.66	2.35	19.14	3.25	15792.57	0.38	71.76	250.36
45	367.14	8.77	543.41	1.96	0.17	39.81	0.18	1.59	2.26	0.78	11.22	3.58	42.46	17.05	84.14	21.26	221.04	45.22	12363.54	1.38	220.17	152.92
46	615.63	9.55	1592.04	2.76	0.01	25.75	0.12	2.49	5.96	1.64	35.26	11.78	147.99	57.32	233.56	56.27	529.64	97.11	11359.32	1.54	170.49	164.05
47	579.44	191.84	1210.00	6.71	1.75	51.95	1.79	11.03	10.75	7.93	39.80	12.81	131.85	38.90	158.88	34.46	327.82	57.83	10690.45	1.52	589.13	650.37
48	849.42	2.82	1559.40	1.45	2.88	18.86	1.21	8.78	8.03	0.79	37.65	12.26	142.93	53.63	235.16	53.07	488.84	86.06	12673.42	1.11	484.67	623.43
49	522.55	4.96	1041.78	2.43	0.05	23.19	0.09	2.03	3.62	1.27	20.63	6.74	85.29	34.18	158.72	38.00	375.62	76.89	11625.64	1.02	311.34	257.77
50	604.82	11.10	1800.13	2.56	0.91	19.93	0.81	6.06	16.25	2.00	33.70	12.68	155.82	60.75	283.94	66.98	652.92	120.51	13408.19	1.56	343.85	846.52
51	1104.96	17.62	3380.44	98.97	1.38	23.88	1.44	12.25	15.24	3.72	66.06	24.91	323.77	120.47	513.24	106.38	845.45	118.95	8520.45	24.47	882.56	1172.81
52	379.33	4.72	537.57	2.44	0.07	5.23	0.16	0.98	1.31	0.62	8.30	3.02	39.61	16.66	83.59	21.07	224.15	46.07	14606.99	3.60	171.82	1020.19
53	651.34	14.99	2420.16	7.62	2.73	97.67	2.22	17.95	19.72	6.85	71.35	22.28	240.14	83.21	355.60	78.36	717.31	126.43	10338.89	3.10	990.44	691.36
54	673.27	19.70	1761.69	4.31	4.38	39.75	4.89	33.73	28.43	16.96	73.60	21.69	209.25	62.89	238.75	49.32	420.31	66.20	11505.92	1.78	734.34	1771.21
55	45834.06	9.64	4687.90	4.04	277.23	691.47	114.47	633.82	264.47	16.99	413.24	85.44	649.75	161.68	522.85	90.50	656.44	96.82	11347.33	3.24	528.27	953.34
56	507.97	5.32	1560.93	3.59	0.10	8.35	0.26	4.08	7.95	0.43	42.32	14.05	156.19	56.49	235.21	48.93	420.09	72.14	12608.43	1.74	280.29	748.57
57	563.07	8.24	2305.26	3.70	0.09	9.34	0.16	3.56	8.17	0.75	52.48	18.69	226.66	84.90	361.40	76.57	669.92	114.40	11936.84	2.05	233.92	516.98
58	180.45	0.79	29.58	0.15	0.00	0.16	0.01	0.07	0.09	0.05	0.26	0.17	2.73	1.06	4.74	1.20	12.30	2.21	9594.89	0.04	61.99	197.05
59	1088.79	35.73	3758.48	10.68	6.67	56.59	7.97	57.53	54.33	42.34	171.15	55.51	512.84	134.25	469.47	92.54	762.43	117.48	11268.07	7.49	1077.25	1983.44
60	1672.23	20.95	5143.56	16.14	2.83	43.92	4.46	30.12	36.64	43.85	148.04	50.86	552.92	187.21	803.75	180.56	1651.49	293.71	11857.41	6.23	652.95	1533.30
61	897.32	14.58	1114.49	1.31	0.37	2.06	0.51	3.23	4.72	3.13	25.79	11.30	119.07	34.97	135.31	31.24	282.85	47.29	15004.79	2.16	44.72	1619.23
62	339.37	4.36	1269.10	5.28	0.01	5.18	0.03	0.69	2.18	1.43	20.13	8.05	106.51	43.59	201.35	44.30	399.70	72.61	12364.69	1.19	89.49	381.90
63	758.70	3.04	3595.22	6.64	0.06	5.90	0.67	11.19	24.96	11.04	135.22	43.41	439.49	135.59	499.42	95.41	771.82	126.48	10714.46	2.91	61.41	117.34
64	305.95	32.96	532.94	1.40	0.11	24.92	0.39	4.89	6.11	2.38	20.96	5.54	54.34	18.18	75.51	16.73	146.21	27.56	12204.07	0.79	333.01	147.71
65	466.69	8.89	1725.18	4.24	0.13	44.28	0.72	10.48	14.73	5.18	59.60	16.86	180.63	61.76	250.25	52.82	464.16	82.30	9303.54	1.86	565.32	328.23
66	428.85	4.65	1020.34	1.80	1.89	45.29	1.04	11.86	12.65	4.09	47.48	12.04	116.44	36.70	140.82	28.57	246.98	42.50	11698.03	0.97	515.30	185.86
67	558.75	17.81	1146.87	4.42	0.04	5.95	0.07	1.22	3.63	0.13	23.85	9.78	114.66	42.53	165.80	32.87	268.32	45.99	14557.99	1.61	172.13	580.31
68	327.50	17.08	891.61	3.80	0.81	46.36	0.56	8.55	10.19	5.90	35.95	9.47	88.91	28.07	109.34	22.67	204.79	35.94	9305.96	0.76	260.10	318.81
69	521.77	47.77	1907.97	11.16	4.63	95.41	3.38	21.26	18.37	13.17	55.75	17.45	188.57	64.38	280.74	65.01	624.92	116.09	10780.00	2.73	1566.75	1190.17
70	346.47	6.66	128.70	0.66	0.01	0.38	0.06	1.04	3.54	0.16	15.08	3.52	23.60	4.22	9.99	1.44	10.49	1.43	14893.03	0.45	55.16	500.55
71	2403.09	6.33	725.31	0.83	8.04	70.32	5.24	35.34	15.62	6.14	31.43	7.40	65.14	20.61	86.18	19.29	188.74	37.46	8844.10	0.19	232.46	667.89
72	1723.01	28.04	3926.72	5.10	9.19	42.79	10.80	69.33	57.53	38.24	150.01	48.42	484.17	134.32	466.22	86.71	660.60	93.23	15018.54	2.54	807.25	3447.54
73	402.36	30.07	1337.78	1.25	0.12	28.18	0.59	8.86	11.36	4.11	46.46	14.33	142.52	47.45	191.85	40.90	368.03	63.26	9317.10	0.70	291.52	98.69
74	864.15	33.51	1417.94	1.93	8.14	24.31	2.51	14.64	8.64	0.83	38.79	12.06	138.99	50.54	213.76	45.02	389.03	66.76	10383.52	1.10	122.12	169.52
75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.42
76	475.24	10.25	3029.11	1.08	0.02	3.32	0.29	5.44	12.40	0.69	76.18	26.59	317.38	115.76	477.38	97.08	823.98	138.01	10675.39	0.47	227.88	348.01
77	529.55	82.22	1858.29	10.34	1.98	42.54	3.53	27.04	32.61	45.40	84.00	24.02	219.05	60.37	225.94	47.98	435.48	77.12	10353.52	2.18	429.27	1038.40
78	782.75	12.93	1547.20	10.90	0.75	8.82	0.48	3.64	5.40	2.57	38.26	14.63	167.29	53.11	202.28	42.44	391.91	71.46	11792.83	9.71	37.48	216.97
79	676.29	10.28	1356.76	0.68	0.00	3.18	0.10	2.06	5.54	0.17	32.62	11.02	131.04	47.71	206.22	45.22	411.94	69.59	13419.39	0.58	128.14	245.38
80	525.17	6.90	3135.43	10.15	0.07	23.51	0.39	6.52	16.84	3.86	86.98	30.32	345.67	120.68	479.07	96.12	793.97	124.42	9715.49	4.82	145.96	213.91

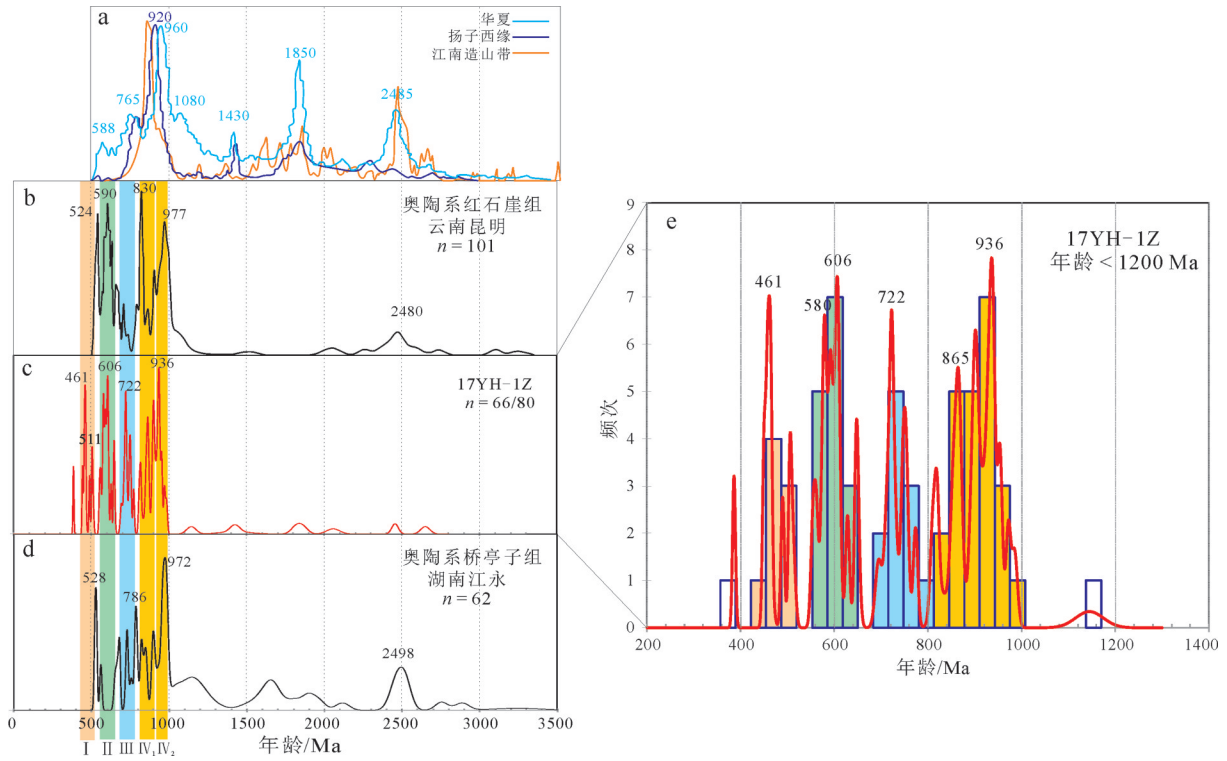


图4 沿河县湄潭组碎屑锆石年龄频率分布图及与区域相当层位的对比

a—邻近地区前寒武纪碎屑锆石年龄谱;b—云南昆明奥陶系红石崖组碎屑锆石年龄谱;c—贵州沿河湄潭组碎屑锆石年龄谱;d—湖南江永奥陶系桥亭子组碎屑锆石年龄谱;e—贵州沿河湄潭组碎屑锆石年龄频率分布图(图c的局部放大)

Fig. 4 Relative probability plots of detrital zircon sample from the Meitan Formation in Yanhe County, and correlation with its equivalent strata.

a—Detrital zircon age spectra of Precambrian near the study area; b— Detrital zircon age spectra of the Hongshiya Formation in Kunming, Yunnan; c— Detrital zircon age spectra of the Meitan Formation in this study; d— Detrital zircon age spectra of the Qiaotingzi Formation in Jiangyong, Hunan; e—Enlargement of Fig. c

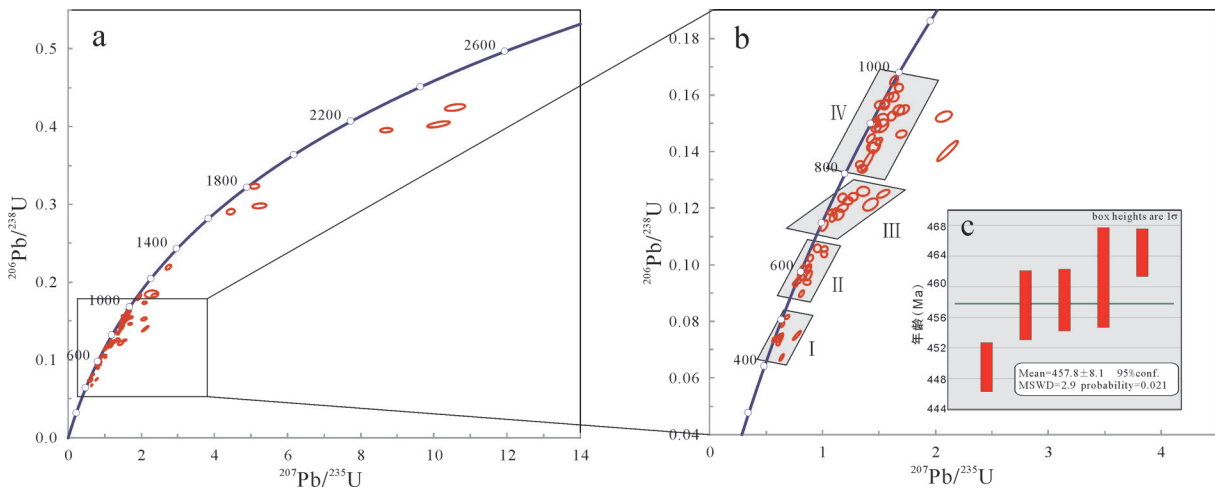


图5 沿河县湄潭组碎屑锆石谐和图及变质年龄分析

(图a,b为4组年龄谐和图中的分布,图c为最年轻1组锆石的加权平均年龄)

Fig. 5 Concordia diagram of detrital zircon and the analyses of metamorphic age from the Meitan Formation in Yanhe County (Figs. a and b show the distribution of age range in concordia diagram; Fig. c shows the weighted average age of the youngest group)

于交点年龄地质意义,这种对应关系也可能只是巧合,尤其第Ⅲ组年龄和年龄最老的2颗锆石之间,缺少落在不一致线上的年龄点。因此,下文将继续结合锆石微量元素等对各组物源做进一步辨别分析。

4.2 锆石成因分析

研究表明,岩浆锆石通常具有Ce正异常、Eu负异常、Sm/Ce比值很大的特点,而热液锆石则Ce和Eu异常均不明显,Sm/Ce比值很小(Hoskin et al., 2005),在稀土元素配分曲线中,热液锆石的显得相对平坦,但稀土总量往往较高。从样品的稀土元素配分曲线(图6a)可以看出,确有一部分曲线符合热液锆石的特征,说明样品中有一部分锆石受到了热液作用的影响。但由于这些锆石均有不同程度的磨圆,因此可以认为它们是在物源区受到热液作用的改造之后,再旋回沉积到湄潭组之中的。

更进一步地,我们挑出了所有具Eu正异常的锆石颗粒(图6b,表2),发现具Eu正异常的锆石绝大部分都在第Ⅰ组年龄范围内,少量分布在第Ⅲ组和Ⅳ₁组中,而在第Ⅱ组和第Ⅳ₂组中缺失(图6b),且在第Ⅰ组锆石中,热液锆石的占比高达73%。这说明热液作用主要发生于第Ⅰ组锆石年龄期间(450~511 Ma),第Ⅱ组第Ⅳ₂组锆石没有受同期热液作用的影响,暗示第Ⅱ组和第Ⅳ₂组锆石与其他3组锆石的物源区不同。通常来说,变质锆石一般Th/U比值小于0.1,岩浆锆石一般大于0.4(吴元保等,2004),样品中各组锆石的Th/U比值大体相似,仅第二组锆石的Th/U比值总体略偏低,也支持了第Ⅱ组锆石的不同起源。

因此,结合上面对铅丢失程度的分析,认为湄潭组的物源应分为3部分,第Ⅰ组、第Ⅱ组和第Ⅳ₂组、第Ⅲ和Ⅳ₁组,分别来自不同的物源区,其中第Ⅲ组和Ⅳ₁组可能来自同一物源区变质程度不同的部位。

4.3 对热液成矿年代学的启示

热液成矿方面,区域地质调查发现,在黔东北(沿河)—渝东南(酉阳)一带广泛发育萤石、重晶石及铅锌(汞)矿化,张遵遵等(2018b)以黔东北沿河大竹园萤石矿床为研究对象,分别利用萤石和方解石单矿物Sm-Nd等时线方法,获得大竹园萤石矿成矿年龄为早志留世(430~436 Ma),与湘西—黔东MVT铅锌矿床成矿时代(410~477 Ma)一致(王华云,1993;段其发等,2014;杨红梅等,2015;于玉帅

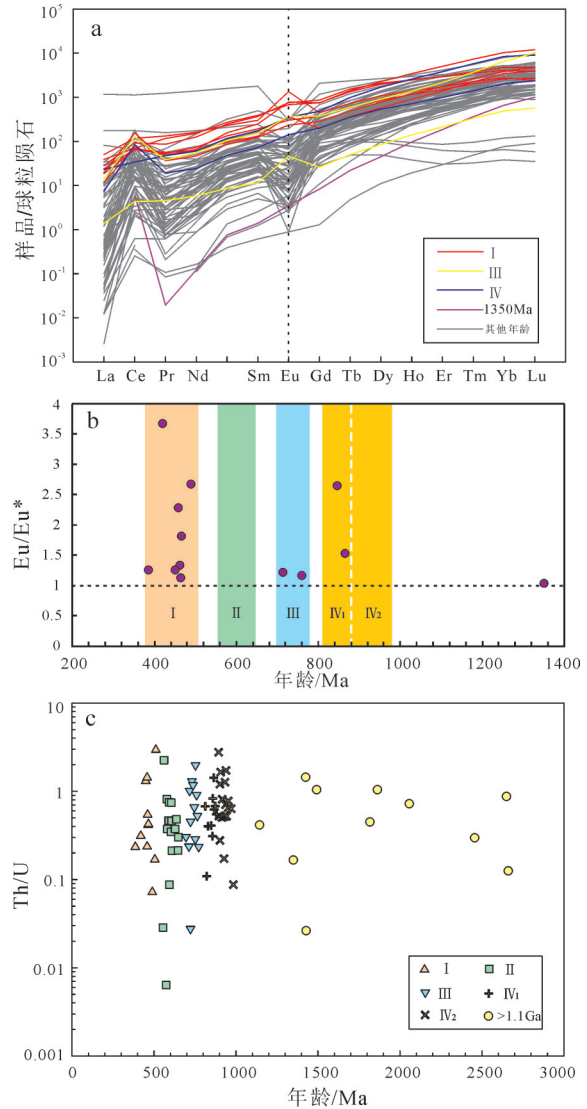


图6 沿河县湄潭组碎屑锆石稀土元素配分曲线(a)、Eu异常分布图(b)、Th/U比值分布(c)

Fig.6 Plot of REE patterns (a), Eu anomaly (b) and ratio of Th/U (c) from detrital zircon sample of the Yanhe Formation, Yanhe County

等,2017)。这些年龄与本文的第Ⅰ组年龄(450~511 Ma)及变质年龄(443 Ma)不谋而合、相互印证,从而从侧面表明了该期热液活动影响的广泛性,即不仅在发生沉积的沿河地区形成了低温热液矿床,还对邻近的物源区碎屑产生了不同程度的影响(图7),暗示此时加里东运动已经开始波及中上扬子沿河地区,但主要表现为热液活动,并没有发生大规模岩浆作用。另外,从前人成果来看,较少发现形成于477~511 Ma的矿床,同期热液活动为何有的时段见矿,有的时段却不见,究竟是未成矿还是未发

现,也有待进一步研究。

4.4 对古地理的启示

根据前人研究,中上扬子震旦纪—志留纪克拉通盆地经历了由伸展到挤压的两大阶段,而发生转换的时期恰好是中奥陶世前后(刘宝珺等,1993;黄福喜等,2011;何垚砚等,2016),并于张家界—吉首一带形成隆起(黄乐清等,2018),称为武陵—雪峰隆起带(即江南造山带),该带经历了晋宁运动的岩浆活动和随后的南华裂谷期沉积,可分别为沿河地区湄潭组提供第Ⅲ组和Ⅳ₁组年龄的物源,是碎屑物源再旋回的主要载体。并且,研究区热液流体的活跃可能就跟这种从伸展—挤压的构造体制转换有关。

扬子块体西部有一个显著的年龄峰值920 Ma,而华夏块体的最显著峰值为960 Ma,并且有较多1000~1200 Ma的锆石(图4a),这两个峰值年龄在样品17YH-1Z中均有记录(图4c),但仅有1颗锆石年龄(1144 Ma)落在1000~1200 Ma(表1),因此,推测第Ⅳ₂组物源主要来自扬子西缘。在同期地层的对比中,第Ⅱ组锆石桥亭子组较少有记录,而在红石崖组中形成显著峰值,因此认为该组年龄也主要来源于扬子西缘,这与前述第Ⅱ组和第Ⅳ₂组辨别为同一部分的分析结果一致,进一步印证了扬子西缘作为沿河地区湄潭组物源区的可能性。湄潭组岩性

在纵向上自下而上、横向上自西向东表现为碎屑减少、钙质增加的特征(Chen et al., 1995;汪啸风等,1996;陈朋飞等,2006),与碎屑由近源—远源的特征相符,具备提供物源的地质基础。结合前人古地理研究(周恩恩和许效松,2016;周恩恩等,2016),认为湄潭组中出现的碎屑物质有一部分是康滇古陆逐步扩展的产物。另外,红石崖组和桥亭子组分别显示了524 Ma和528 Ma两个十分相近的显著峰值(图4b、d),但是在本文的样品中却几乎没有记录(图4c),可能是受热液作用改造的影响。

另一方面,第Ⅱ组和第Ⅳ₂组碎屑年龄虽然在华南缺乏相应的成岩母体,但是在武陵—雪峰隆起的南东(即扬子东南缘和华夏地区)的碎屑岩中发现了大量该时期的碎屑锆石(Yao et al., 2015;张雄等,2016;Xiong et al., 2018),且有古流向研究表明,与研究区同处武陵—雪峰隆起带北西一侧的湘西北台地相区,其陆源物质来源于南边(黄乐清等,2018)。所以,笔者认为武陵—雪峰隆起的南东方向的物源区对第Ⅱ组和第Ⅳ₂组年龄的碎屑也有微弱贡献,而之所以能够穿越武陵—雪峰隆起带而到达沿河地区,可能与Yu et al.(2015)通过对邻近地区的早志留世碎屑锆石样品的研究得出的认识类似:因为武陵—雪峰隆起带并没有完全连成一片,不构

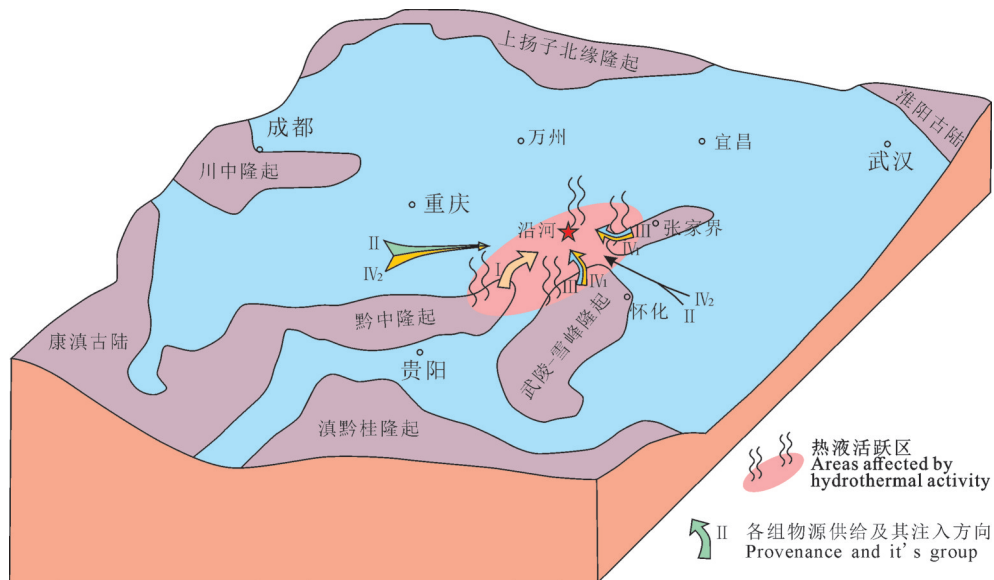


图7 沿河地区中奥陶统湄潭组沉积时期物源组成及热液影响示意图(据黄福喜等,2011;黄乐清等,2018修改)

Fig.7 Schematic diagram of provenance and hydrothermal area in the Yanhe area during the depositional time of the Meitan Formation, middle Ordovician (modified from Huang Fuxi et al., 2011 and Huang Leqing et al., 2018)

The region defined by the pink ellipse has affected by the hydrothermal activity; the arrows represent provenance of detritus

成一个连续的物源阻隔,而是呈岛状串联,其间有沟通两侧的水流通道(图7)。说明至少在中奥陶世—早志留世,武陵—雪峰隆起保持了这样不连续分布的状态。

同时,位于研究区南部的黔中隆起也在逐渐发展,黔中隆起通常是指遵义一带以南奥陶—志留纪的一个东西向隆起,最早由尹赞勋于1949年提出。前人关于黔中隆起的研究成果较多,多数学者认同古隆起经历了水下和水上两个阶段,只是对水陆转换发生的时间有不同意见,主要有中奥陶世(沈志达等,1990;梅冥相,1994)和晚奥陶世(牛新生等,2007;邓新等,2010)两种观点。由前述分析可知,第I组锆石年龄应来源于与上述两处不同的物源区,结合前人的隆起分布来看,第I组碎屑只可能是来自于黔中隆起这一新隆升的物源区。因此,笔者认为黔中隆起此时即便没有隆升成陆,也达到了浪基面附近的可剥蚀区间,从而为湄潭组提供了近乎同沉积且包含较多热液锆石的碎屑物源。

5 结 论

根据湄潭组碎屑锆石年龄的分布和特征峰值,可将其分为5组:~461 Ma(I)、~580 Ma和~606 Ma(II)、~722 Ma(III)、~865 Ma(IV₁)和~936 Ma(IV₂)。再通过对锆石同位素比值、稀土元素等的分析,认为其物源主要分为3部分,第I组、第II组和第IV₂组、第III和IV₁组,分别主要来自3个不同的物源区。结合前人研究,认为这3个物源区分别是黔中隆起、扬子西缘康滇古陆(另有少量来自扬子东南缘—华夏地区)、武陵—雪峰隆起。其中黔中隆起和武陵—雪峰隆起是两个新隆升的物源区,当然,需要说明的是,物源供给是一个复杂的系统,这里仅示意了其主要的供给区。

对湄潭组碎屑锆石的稀土元素研究发现,第I组年龄450~511 Ma范围内发育了大量热液锆石,与区域低温热液成矿时间对应,认为其形成是物源区流体的活跃导致的,可能跟奥陶纪区域构造体制的转换有关,暗示此时加里东运动已经开始波及中扬子沿河地区,但主要表现为热液活动,并没有发生大规模岩浆作用。

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