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皖南地区北东向断裂左行走滑时代及构造背景讨论

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提要:皖南地区地处扬子板块的东部,晚中生代发育多期与古太平洋板块俯冲有关的岩浆活动及构造变形。其中北东向断裂作为控制构造格架的重要断裂,自印支期以来经历了多期演化。前人多集中于探讨断裂的活动期次,对于各期活动时限的研究存在争论,这恰恰是制约深入研究皖南地区乃至中国东部中生代以来构造演化的关键。本文通过野外调查发现北东向断裂的左行走滑表现为高角度平移断层,古构造应力场反演指示其形成于NNE−SSW向挤压环境,锆石U−Pb年代学及地层切割关系指示皖南地区左行走滑时代为早白垩世末期。结合前人古生物、地层等方面研究,认为皖南地区左行走滑活动时限应在121 ~ 110 Ma。该期活动或与早白垩世末期伊泽奈崎板块运动方向的改变有关。

关 键 词:晚中生代;左行走滑;年代学;地质调查工程;皖南

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Discussion on the sinistral strike−slip age and tectonic background of north−east fault in southern Anhui Province

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Abstract: Lying in the east of the Yangtze plate, southern Anhui experienced multiple periods of magmatic activity and tectonic deformation related to the subduction of the Paleo−Pacific Plate during the late Mesozoic. As an important structure controlling the tectonic framework, the NE−trending fault has undergone multiple stages of evolution since the Indosinian period. Previous studies mainly focused on the active stages of faults, and there were disputes on the active periods of each stage, which restricted the in−depth study of tectonic evolution in southern Anhui and even eastern China since Mesozoic. The field investigation reveals that sinistral strike− slip deformation of the NE− trending fault in southern Anhui is actually a high− angle translational fault. The inversion of the paleo−tectonic stress field indicates that it was formed in the NNE−SSW compression environment. Zircon U−Pb

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geochronology and stratigraphic cutting relationship indicate that its sinistral strike−slip age is at the end of Early Cretaceous. Combined with previous studies on paleontology and stratigraphy, it is believed that its sinistral strike slipping was formed in 121−110Ma, and may be related to the movement direction change of the Izenizaki Plate at the end of the Early Cretaceous.

Key words: Late Mesozoic; sinistral strike−slip; chronology; geological survey engineering; southern Anhui

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1 引 言

中国东部地区在中生代广泛发育与古太平洋板块俯冲有关的岩浆作用和构造变形(Zhou and Li, 2000; Li and Li, 2007)。期间太平洋板块在向华南陆块俯冲过程中发生了角度和方向的变化(Engebretson et al., 1985; Maruyama et al., 1997; Zhou and Li, 2000; Li and Li, 2007; Liu et al., 2012),导致中生代以来中国东部地区构造应力场发生多次变化(余心起等, 2005; 舒良树, 2012; 万天丰等, 2012; 张岳桥等, 2012; 朱光等, 2018; 李三忠等, 2018;宋传中等,2019),引发不同方向断裂系多期次、不同力学性质的构造活动(张岳桥等, 2007; 索艳惠等, 2013; 李三忠等, 2017; 朱光等, 2018)。其中北东向断裂作为该时期重要的控岩、控相、控矿断裂,更是众多学者研究的重点,并在活动期次、力学性质及控岩、控矿等方面获得诸多成果(朱光等, 1998; 宋传中等, 2010; 舒良树, 2012; 常印佛等, 2012; 江来利等, 2016; 周涛发等, 2017; 李三忠等, 2018),但对于断裂活动时限的研究相对较少,导致不同期次活动的年代跨度相对模糊,这恰恰是制约深入研究中国东部中生代以来构造演化的关键。

皖南地区地处江南造山带东段,夹持于华北陆块与华夏地块之间,自中—新元古代以来经历了多期次造山活动(邢凤鸣等, 1992; 朱光等, 2000; 余心起等, 2006; 戴圣潜等, 2006; 薛怀民等, 2010),并在燕山期先后受伊泽奈崎板块及太平洋板块俯冲作用的影响,引发大规模的断裂活动及岩浆侵位。期间北东向断裂保留了逆冲挤压(推覆)、高角度正断拉张,左行平移、右行平移等多期次构造活动的证据(刘国生, 1997; 万天丰等, 2012; 江来利等, 2016; 朱光等, 2016; 杨明桂等, 2016)。

本文针对皖南地区北东向断裂左行走滑活动的调查中除发现该期断裂切割、破坏诸如旌德、榔桥等早白垩世岩体及后期岩脉外,还在早白垩世晚期杨湾组内发现有同期活动的断面擦痕,说明早白垩世伸展与岩浆活动之后叠加了该期左行走滑活动。故本文以野外地质现象为基础,利用杨湾组内部碎屑锆石年龄及构造应力场反演两种方法,结合前人在中国东部区域构造应力场、古生物化石及白垩纪红层的研究成果,综合判断该期构造活动的时限,以期为皖南地区乃至中国东部的断裂序次、岩浆、成矿等后续研究提供年代学支撑。

2 地质背景

皖南地区地处安徽南部,大地构造位置处于晋宁期以来江南造山带北侧的下扬子前陆盆地内,北临高坦断裂,南以江南隆起带为界。区内又以江南断裂为界划分为两个次级构造单元,即东至—泾县冲断带及宁国—太平褶冲带。出露地层包括南华—震旦纪形成的碎屑岩、泥岩、碳酸盐岩、硅质岩组合,寒武—志留纪的一套碳酸盐岩、泥岩、碎屑岩组合,泥盆—三叠纪碎屑岩、碳酸盐岩、泥岩、硅质岩,以及中新生代以来的砾砂岩组合(图1)。

区内褶皱行迹主要为印支—燕山期构造活动的产物,以发育大型复式背、向斜为特征,包括贵池复向斜、七都—横百岭复背斜、太平复向斜及宁国—绩溪复背斜。断裂行迹复杂,按形成时代大致可分为印支—燕山早期近东西、北东向断裂,燕山中晚期北北东、北西向断裂,喜山期近南北向断裂,晚期断裂往往切割、破坏早期断裂。区内大型断裂包括高坦断裂、江南断裂、周王断裂、汤口断裂、绩溪断裂、祁门—潜口断裂。

岩浆岩主要为晋宁期及燕山期两期岩浆作用产物。前者时代集中于860～820 Ma和780～740 Ma(李献华等, 2002; 吴荣新等, 2005,2007; Wang et al., 2007; 薛怀民等, 2010; Zhang et al., 2012; 闫俊等, 2017),后者时代集中于152～136 Ma和136～

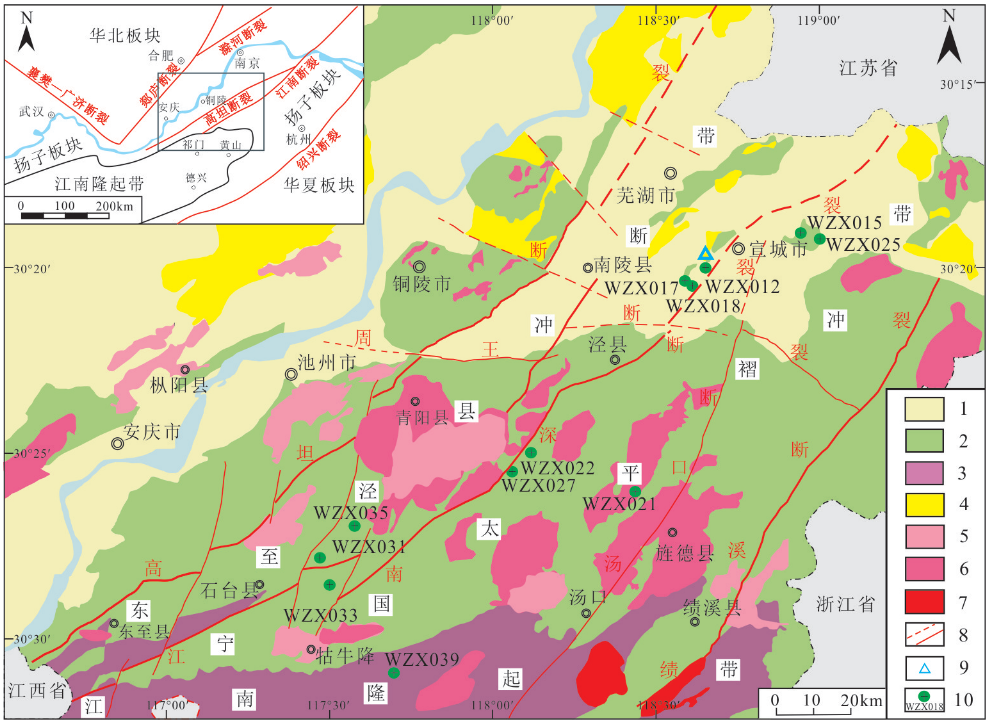

图1 研究区大地构造位置图

1—燕山—喜山构造层; 2—加里东—印支构造层; 3—四堡—晋宁构造层; 4—早白垩世晚期火山岩; 5—早白垩世晚期花岗岩; 6—早白垩世早期花岗岩; 7—新远古代花岗岩; 8—断层; 9—采样位置; 10—野外观察点位置

Fig.1 Geotectonic map of the study area

1−Yanshan−Himalayan structure layer; 2−Caledonian−Indosinian structure layer; 3−Sibao−Jinning structure layer;4−Late Early cretaceous volcanic rocks; 5−Late Early cretaceous granites; 6−Early period of Early Cretaceous granite; 7−Neoproterozoic granite; 8−Faults; 9−Sample locations; 10−Field observation position

122 Ma(薛怀明等, 2009; 周翔等, 2011, 2012; Wang et al., 2012; Wu et al., 2012; 谢建成等, 2012),岩性以花岗闪长岩及二长花岗岩、正长花岗岩为代表的中酸性侵入岩。

3 左行平移构造

皖南地区断裂构造发育,按断裂方向可划分为北东东—近东西向、北东向、北西向、北北东—近南北向。其中北东向断裂作为该区中控制构造格架的主干断裂,在区域演化过程中表现出多期次、不同性质的力学活动,大致包括早期逆冲、较早期拉张、中期走滑、中晚期右行走滑拉张及晚期逆冲挤压。

研究区内北东向左行走滑构造变形主要表现为高角度的左行平移断层,除发育于新元古代—晚中生代地层内,还左行错断早白垩世中酸性侵入岩(图2a~h)。通过对皖南地区江南断裂带及其旁侧次级断裂系统性观察,发现该期断裂的断层面倾向以南东居多,少数倾向北西,倾角较陡(>45°)。断层面发育近水平或小角度(<25°)斜向擦痕,切割印支—燕山早期逆冲断层及燕山中期的正断层,后被燕山晚期具右行走滑性质的正断层所切割(图2i)。次级断裂还发育有宽数米的压性走滑破碎带,带内构造岩以断层泥、碎裂岩、角砾岩为主(图2j),两盘还伴生有指示左行走滑的倾竖褶皱(图2k)。

通过对上述区内北东向断裂滑移矢量的测量和统计(表1),反演了其构造古应力场,断层滑移数据分析构造应力场依据野外断面测量的滑移数据模拟岩石该期构造活动的应力状态,并重建、简化的应力张量(Angelier, 1994; Delvaux and Sperner, 2003)。4个变量分别为3个轴向互相垂直的主应力($\sigma1$,$\sigma2$,$\sigma3$)以及表示$\sigma2$相对于$\sigma1$和$\sigma3$大小关系的应力比(R),其中$\sigma1\geq\sigma2\geq\sigma3$,$R=(\sigma2-\sigma3)/(\sigma1-\sigma3)$。野外采集数据包括断面产状,擦痕产状及运动方向(Petit, 1987; Angelier, 1989),在室内利用Win−

图2 皖南地区北东向断裂左行走滑断面照片

a—早白垩世中晚期花岗斑岩左行平移擦痕; b—早白垩世杨湾组左行平移擦痕; c—早白垩世花岗闪长岩左行平移擦痕; d—早白垩世中分村组左行平移擦痕; e—中志留世唐家坞组断面左行平移擦痕; f—早志留世康山组断面左行平移擦痕; g—奥陶纪长坞组左行平移擦痕; h—南华纪休宁组左行平移擦痕; i—早白垩世中晚期花岗斑岩右行正断擦痕切割早期左行平移擦痕; j—早志留世坟头组内部左行平移断裂; k—左行走滑断裂旁侧倾竖褶皱; l—晚白垩世赤山组覆盖于左行走滑破碎带

Fig.2 Photographs showing the section of the sinistral strike−slip NE−trending fault in southern Anhui

a−Sinistral translational scratches of granitic porphyry in Middle and late Early Cretaceous; b−Sinistral translational scratches of Yangwan Formation in Early Cretaceous; c− Sinistral translational scratches of granodiorite in Early Cretaceous; d− Sinistral translational scratches of Zhongfencun Formation in Early Cretaceous; e−Sinistral translational scratches of Tangjiawu Formation in Middle Silurian; f−Sinistral translational scratches of Kangshan Formation in Early Silurian; g−Sinistral translational scratches of Changwu Formation in Ordovician; h−Sinistral translational scratches of Xiuning Formation in Nanhua period; i−Dextral normal fault scratches cutting sinistral translational scratches of granitic porphyry in middle and late Early Cretaceous; j−Sinistral translational scratches of Fentou formation in Early Silurian; k−Sinistral strike−slip fault lateral to a vertical fold; l−Chishan Formation of the Late Cretaceous covering the sinistral strike−slip fracture zone

Tensor软件(Delvaux and Sperner,2003)进行古构造应力场反演。

高角度脆性左行走滑断裂除切过南华纪至早白垩世地层外,还在早白垩世岩浆岩及同期陆相碎屑地层保留有该期断裂活动的断面擦痕,零星可见该期活动形成的压性破碎带被晚白垩世赤山组所覆盖(图2l),指示在上述岩体冷凝、地层沉积之后发生该期左行走滑活动,而由主断面中擦痕、阶步及方解石或石英擦抹晶体等证据均指示其运动学性质为脆性左行走滑,构造古应力场表明为高角度脆性走滑断裂形成于NNE-SSW向的挤压环境(图3)。

4 LA-ICP-MS锆石U-Pb年代学

4.1 杨湾组基本特征

杨湾组由安徽区调队(1974)创名于铜陵市枞阳县杨湾村,主要分布于沿江盆地及宣广盆地中。岩性以紫红色块状砾岩、含砾粗砂岩夹紫红色厚层粉砂岩为主,向上过渡为紫红色钙质细砂岩、含钙质粉砂质泥岩夹含凝灰质中细砂岩。介形类、轮藻及叶肢介碎片等化石显示本组时代为早白垩世晚期。

该组与下伏早白垩世中期中分村组(K_1zf)灰白色熔结凝灰岩、含集块火山角砾岩呈角度不整合接触,与上覆晚白垩世早期七房村组(K_2qf)灰紫、浅灰色厚层砂砾岩呈角度不整合接触。

本研究建立在野外详细观察的基础上,于宣城市郭村一带的杨湾组内采集了2组含凝灰质细砂岩进行锆石U-Pb年代学测试。

4.2 测试方法

锆石制靶、阴极发光图像(CL)采集以及LA-ICP-MS锆石U-Pb定年相关测试分析在南京宏创地质勘查技术服务有限公司内完成。其中锆石制靶首先对锆石样品粉碎后进行标准磁选和重选,再在双目镜下进行挑纯,将挑选出的锆石颗粒用环氧树脂交接,待固结后细磨至锆石颗粒核部出露,抛光制靶以待分析。阴极发光(CL)图像是了解锆石内部结构并作为锆石年龄测试选点的依据。

锆石激光锆石激光剥蚀-等离子质谱(LA-ICP-MS)采用安捷伦科技(Agilent Technologies)制造公司生产的Agilent 7700x ICP-MS测定,激光剥蚀系统为Australian Scientific Instruments公司的Resolution LR。测试中使用的激光束斑直径为33 μm。锆石U-Pb年龄测试过程中采用国际标准锆

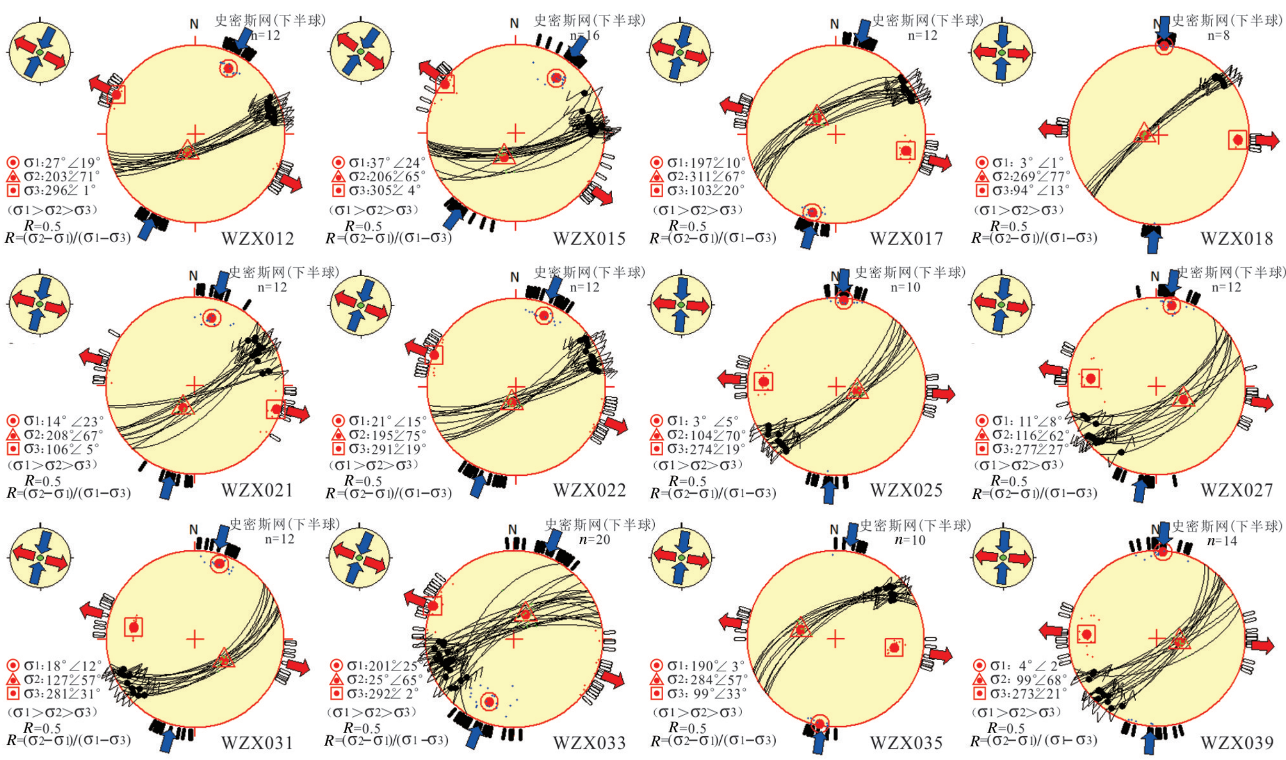

图3 皖南地区高角度左行平移断裂构造古应力场反演

Fig.3 Inversion of paleo-stress field for high-angular sinistral strike-slip fault in Southern Anhui

表1 皖南地区左行走滑断层实测滑移矢量数据

Table 1 Strike−slip vector data of sinistral faults in southern Anhui

断层面产状/°		擦痕/线理产状/°		断层面产状/°		擦痕/线理产状/°	
倾向	倾角	倾伏向	倾伏角	倾向	倾角	倾伏向	倾伏角
点号:WZX012 地点:宣城市宣州区 GPS:20658280 3427315 发育地层:K_1y 性质:左行平移							
160	80	83	8	165	74	79	14
164	72	78	10	169	77	82	12
155	79	67	12	154	81	66	13
157	82	69	15	161	74	74	9
160	71	76	17	157	72	72	15
167	76	80	12	152	75	64	7
点号:WZX015 地点:宣城市麻姑山 GPS:20681520 3429555 发育地层:K_1zf 性质:左行平移							
175	77	88	12	166	74	82	19
173	68	85	3	174	76	88	15
174	71	87	11	171	72	86	15
169	73	84	16	166	75	80	16
168	68	85	18	171	76	85	14
174	70	89	13	175	71	91	16
173	54	86	4	156	58	78	18
150	63	72	22	148	76	60	12
点号:WZX017 地点:芜湖市南陵县珩琅山 GPS:20642755 3425900 发育地层:S_1f 性质:逆左行平移							
335	67	61	7	328	72	55	8
322	69	51	5	321	60	50	5
337	63	64	8	335	77	63	6
331	66	58	8	340	65	64	8
334	62	57	11	333	76	60	7
337	79	63	7	324	68	52	5
点号:WZX018 地点:芜湖市南陵县珩琅山 GPS:20642772 3426015 发育地层:$\gamma\pi K^1$ 性质:左行平移							
321	86	48	8	318	80	47	7
317	83	45	12	319	81	47	9
316	80	44	11	323	82	52	9
325	81	53	10	316	81	42	10
点号:WZX021 地点:宣城市旌德县三溪镇 GPS:20639669 3363525 发育地层:$\gamma\delta K^1$ 性质:左行平移							
150	85	61	14	135	63	53	17
138	75	52	14	149	82	63	28
146	77	61	19	143	70	58	16
152	75	69	25	167	82	80	23
145	77	62	24	135	80	50	23
166	80	79	16	150	83	63	21
点号:WZX22 地点:宣城市泾县桃花潭镇 GPS:20612723 3375208 发育地层:S_2t 性质:左行平移							
160	80	72	9	156	76	68	9
165	74	78	10	161	78	73	14
142	82	54	12	145	74	57	6
150	78	63	13	168	79	79	7
147	74	60	8	162	82	73	10
164	81	77	13	143	73	55	5
点号:WZX025 地点:宣城市洪林镇 GPS:20688735 3430245 发育地层:S_1k 性质:左行平移							
130	80	215	8	137	68	224	13
140	69	226	12	132	72	220	11
136	77	225	12	150	75	238	11
154	74	242	14	141	68	227	15
143	81	230	17	146	77	235	7
点号:WZX027 地点:黄山市黄山区燕子岭 GPS:20606652 3368422 发育地层:D_3l 性质:左行平移							
145	77	234	6	160	62	238	21
139	74	227	8	142	67	225	15
144	55	225	14	150	58	232	8
147	48	227	11	144	74	231	9
139	72	226	11	163	70	248	13
130	53	208	17	160	75	245	16

续表1

断层面产状/°		擦痕/线理产状/°		断层面产状/°		擦痕/线理产状/°	
倾向	倾角	倾伏向	倾伏角	倾向	倾角	倾伏向	倾伏角
点号:WZX031 地点:池州市石台县贡溪乡 GPS:20554232 3347993 发育地层:O_1l 性质:左行平移							
153	60	238	11	148	61	233	12
159	64	243	18	145	55	229	9
162	59	246	10	160	54	245	8
152	53	228	17	164	62	247	14
141	63	220	15	158	65	242	16
142	57	225	11	161	58	243	11
点号:WZX033 地点:池州市石台县河口乡 GPS:20571078 3341613 发育地层:O_3c 性质:左行平移							
350	75	263	11	313	77	231	32
343	62	265	21	338	85	250	23
335	81	248	19	302	53	232	25
344	83	256	14	336	73	251	16
327	74	241	13	343	82	255	11
320	82	232	11	328	65	247	19
332	70	252	24	332	73	251	28
346	80	258	15	313	69	230	15
352	70	268	17	353	80	267	22
336	65	259	25	328	75	244	21
点号:WZX035 地点:池州市石台县小冲 GPS:20563997 3355366 发育地层:$Є_3y$ 性质:逆左行平移							
330	67	53	18	335	61	57	23
322	73	48	14	324	68	45	20
320	71	40	28	339	60	56	22
338	64	52	24	323	67	43	15
331	65	50	20	337	58	52	20
点号:WZX039 地点:黄山市黟县联光村 GPS:20585771 3325155 发育地层:Nh_1x 性质:左行平移							
135	77	224	5	132	70	218	10
150	83	239	11	138	65	220	16
140	80	227	14	155	78	241	18
126	68	213	6	136	69	220	16
137	72	223	13	141	76	228	13
140	84	228	12	157	75	242	20
123	71	207	15	160	63	241	18

石91500作为外标，校正仪器质量歧视与元素分馏；以标准锆石GJ−1为盲样，检验U−Pb定年数据质量；以NIST SRM 610为外标，以Si为内标标定锆石中的Pb元素含量，以Zr为内标标定锆石中其余微量元素含量(Liu et al., 2010a; Hu et al., 2011)。原始的测试数据经过ICP MS Data Cal软件离线处理完成(Liu et al., 2010a, 2010b)。

4.3 测试结果

本次锆石的原位LA−ICP−MS U−Pb定年分析结果见表2。

凝灰质砂岩内部中锆石无色透明，多呈长柱状，长轴80～200 μm，短轴50～70 μm，长宽比为1∶1～1∶3。锆石晶形以自形为主，绝大多数发育震荡韵律环带，极少数显示为弱分带或无分带(图4a)。本次研究实测锆石数85个，获得谐和度＞90%的点74个。谐和锆石Th、U含量及Th/U比值分别为36.54×10^{-6}～548.51×10^{-6}、51.19×10^{-6}～594.35×10^{-6}、0.33～1.18，Th/U比值全部大于0.1，结合CL图像可知该凝灰质砂岩中的碎屑锆石为典型的岩浆锆石。

85颗锆石$^{206}Pb/^{238}U$年龄范围在121.1～581.9 Ma(图4b)，样品中最年轻的碎屑锆石谐和年龄为121.1 Ma，该锆石具有明显的震荡环带，其长宽比约为2∶1，Th/U比值为0.67，为典型的岩浆锆石，表明杨湾组的沉积时代应晚于121.1 Ma。样品中最老的碎屑锆石谐和年龄为581.9 Ma，该粒锆石呈细长柱状，磨圆极差，长宽比＞3∶1，Th/U比值为0.34，震荡环带明显，为典型的岩浆锆石,表明杨湾组的源区保存有极少量新元古代晚期地壳物质的信息。而66个锆石U−Pb年龄集中于121～140 Ma，表明杨湾组的物源部分来自于早白垩世早期的岩浆岩(图4c、图4d)。

由于锆石U−Pb同位素封闭温度在(750±50)℃，碎屑锆石同位素比值不受沉积循环过程中各种分异作用影响，因而其年龄反映物源时代，其中最年轻的单颗粒碎屑锆石年龄通常被用来限定沉积地

表2 杨湾组凝灰质砂岩LA−ICP−MS锆石U−Pb年代学分析结果

Table 2 LA−ICP−MS U−Pb dating result of zircon from sandstone of Yangwan Formation

测点号	元素含量/10^{-6}			Th/U	同位素比值						年龄/Ma					
	Pb	Th	U		$^{207}Pb/^{206}Pb$	±1σ	$^{207}Pb/^{235}U$	±1σ	$^{206}Pb/^{238}U$	±1σ	$^{207}Pb/^{235}U$	±1σ	$^{206}Pb/^{238}U$	±1σ	$^{207}Pb/^{206}Pb$	±1σ
YW-1-01	5.15	113.50	189.20	0.60	0.04902	0.00297	0.13338	0.00778	0.02023	0.00046	127.1	7.0	129.1	2.9	150.1	-58.3
YW-1-02	7.12	145.36	267.75	0.54	0.05020	0.00240	0.13876	0.00655	0.02017	0.00032	131.9	5.8	128.7	2.0	211.2	111.1
YW-1-03	7.73	194.09	278.08	0.70	0.04791	0.00285	0.13243	0.00796	0.02015	0.00041	126.3	7.1	128.6	2.6	94.5	137.0
YW-1-04	6.21	160.66	227.84	0.71	0.04856	0.00220	0.13145	0.00577	0.01975	0.00034	125.4	5.2	126.1	2.2	127.9	107.4
YW-1-05	1.42	36.54	51.19	0.71	0.04955	0.00711	0.12850	0.01720	0.01988	0.00054	122.8	15.5	126.9	3.4	172.3	307.4
YW-1-06	9.73	183.24	372.71	0.49	0.05024	0.00148	0.13695	0.00451	0.01978	0.00038	130.3	4.0	126.3	2.4	205.6	36.1
YW-1-07	5.97	155.92	219.70	0.71	0.05003	0.00209	0.13484	0.00587	0.01961	0.00031	128.4	5.3	125.2	2.0	198.2	100.9
YW-1-08	13.50	399.40	479.33	0.83	0.04998	0.00179	0.13381	0.00455	0.01956	0.00038	127.5	4.1	124.9	2.4	194.5	83.3
YW-1-09	5.52	144.16	202.26	0.71	0.04661	0.00192	0.12707	0.00555	0.01967	0.00031	121.5	5.0	125.6	2.0	27.9	96.3
YW-1-10	11.10	264.23	404.89	0.65	0.05087	0.00173	0.13926	0.00426	0.02005	0.00029	132.4	3.8	128.0	1.8	235.3	84.2
YW-1-11	8.38	211.06	284.46	0.74	0.04950	0.00178	0.14392	0.00522	0.02120	0.00028	136.5	4.6	135.3	1.8	172.3	85.2
YW-1-12	20.30	95.76	178.72	0.54	0.10348	0.00202	1.18784	0.02585	0.08324	0.00114	795.0	12.0	515.4	6.8	543.6	11.4
YW-1-14	5.68	136.46	217.26	0.63	0.05028	0.00189	0.13590	0.00522	0.01971	0.00029	129.4	4.7	125.8	1.8	209.3	91.7
YW-1-15	9.16	242.73	322.93	0.75	0.04893	0.00145	0.14024	0.00400	0.02097	0.00029	133.3	3.6	133.8	1.8	142.7	70.4
YW-1-16	6.34	157.31	215.48	0.73	0.05524	0.00245	0.16356	0.00706	0.02177	0.00037	153.8	6.2	138.8	2.3	420.4	98.1
YW-1-17	17.28	49.78	145.20	0.34	0.06380	0.00161	0.83321	0.02440	0.09446	0.00163	615.4	13.5	581.9	9.6	744.5	53.7
YW-1-18	6.48	154.83	201.48	0.77	0.07617	0.00358	0.23173	0.01090	0.02212	0.00040	211.6	9.0	141.0	2.5	1099.7	89.8
YW-1-19	10.14	294.46	380.81	0.77	0.05088	0.00245	0.13651	0.00639	0.01950	0.00033	129.9	5.7	124.5	2.1	235.3	111.1
YW-1-20	6.42	170.79	230.57	0.74	0.04768	0.00273	0.13086	0.00715	0.02025	0.00042	124.9	6.4	129.2	2.7	83.4	129.6
YW-1-21	7.51	182.96	245.62	0.74	0.04911	0.00207	0.15104	0.00601	0.02261	0.00036	142.8	5.3	144.1	2.3	153.8	100.0
YW-1-23	16.36	178.51	356.00	0.50	0.05226	0.00138	0.26960	0.00798	0.03765	0.00079	242.4	6.4	238.3	4.9	298.2	65.7
YW-1-24	5.65	134.94	206.08	0.65	0.04982	0.00251	0.14007	0.00709	0.02034	0.00039	133.1	6.3	129.8	2.5	187.1	116.7
YW-1-26	6.22	91.53	186.52	0.49	0.05446	0.00216	0.19573	0.00845	0.02589	0.00051	181.5	7.2	164.8	3.2	390.8	88.9
YW-1-27	7.77	225.61	277.47	0.81	0.04722	0.00280	0.12637	0.00698	0.01968	0.00036	120.8	6.3	125.6	2.3	61.2	133.3
YW-1-28	6.90	182.90	251.24	0.73	0.05002	0.00274	0.13614	0.00783	0.01962	0.00032	129.6	7.0	125.2	2.0	194.5	127.8
YW-1-29	6.44	119.72	211.50	0.57	0.05619	0.00261	0.17856	0.00860	0.02320	0.00044	166.8	7.4	147.8	2.8	461.2	103.7
YW-1-30	5.68	132.95	208.40	0.64	0.04902	0.00298	0.13292	0.00731	0.02008	0.00036	126.7	6.6	128.2	2.3	150.1	133.3
YW-1-31	8.55	217.47	304.34	0.71	0.04653	0.00227	0.12906	0.00625	0.02027	0.00033	123.3	5.6	129.4	2.1	33.4	166.6
YW-1-32	9.28	237.48	355.34	0.67	0.04968	0.00218	0.12965	0.00559	0.01896	0.00029	123.8	5.0	121.1	1.9	189.0	101.8
YW-1-33	7.64	206.49	279.40	0.74	0.04687	0.00261	0.12922	0.00752	0.01986	0.00033	123.4	6.8	126.8	2.1	42.7	125.9
YW-1-34	5.85	133.45	207.90	0.64	0.05022	0.00212	0.14317	0.00622	0.02069	0.00033	135.9	5.5	132.0	2.1	205.6	98.1
YW-1-35	7.79	209.12	280.03	0.75	0.04742	0.00194	0.13046	0.00542	0.02006	0.00032	124.5	4.9	128.0	2.0	77.9	87.0
YW-1-36	8.07	180.61	287.18	0.63	0.04877	0.00167	0.13907	0.00495	0.02074	0.00031	132.2	4.4	132.3	2.0	200.1	81.5
YW-1-37	3.27	74.14	114.97	0.64	0.05285	0.00507	0.14223	0.01109	0.02079	0.00047	135.0	9.9	132.6	3.0	320.4	220.3
YW-1-38	8.05	194.40	268.72	0.72	0.05036	0.00191	0.14952	0.00597	0.02157	0.00034	141.5	5.3	137.6	2.1	213.0	88.9
YW-1-39	7.60	195.15	278.48	0.70	0.04906	0.00183	0.13344	0.00491	0.01988	0.00028	127.2	4.4	126.9	1.8	150.1	87.0
YW-1-40	9.48	233.69	346.31	0.67	0.04942	0.00174	0.13482	0.00474	0.01996	0.00031	128.4	4.2	127.4	1.9	168.6	86.1
YW-1-41	7.66	175.16	259.02	0.68	0.05358	0.00182	0.16143	0.00563	0.02199	0.00036	152.0	4.9	140.2	2.3	353.8	75.9
YW-1-42	6.74	169.27	246.70	0.69	0.04998	0.00189	0.13858	0.00559	0.02011	0.00029	131.8	5.0	128.3	1.8	194.5	88.9
YW-1-43	4.96	123.58	172.57	0.72	0.05177	0.00261	0.14970	0.00727	0.02117	0.00038	141.6	6.4	135.1	2.4	276.0	116.7
YW-1-44	7.45	60.27	184.55	0.33	0.06016	0.00213	0.28719	0.01164	0.03444	0.00072	256.3	9.2	218.3	4.5	609.3	75.9
YW-1-45	8.59	210.78	290.03	0.73	0.05385	0.00163	0.15624	0.00481	0.02113	0.00029	147.4	4.2	134.8	1.9	364.9	68.5

续表2

测点号	元素含量/10^{-6}			Th/U	同位素比值						年龄/Ma					
	Pb	Th	U		$^{207}Pb/^{206}Pb$	±1σ	$^{207}Pb/^{235}U$	±1σ	$^{206}Pb/^{238}U$	±1σ	$^{207}Pb/^{235}U$	±1σ	$^{206}Pb/^{238}U$	±1σ	$^{207}Pb/^{206}Pb$	±1σ
YW-2-1	5.44	154.02	197.21	0.78	0.04758	0.00203	0.13124	0.00552	0.02017	0.00033	125.2	5.0	128.7	2.1	79.7	96.3
YW-2-2	7.00	189.61	256.72	0.74	0.04961	0.00188	0.13570	0.00499	0.02000	0.00032	129.2	4.5	127.7	2.0	176.0	87.0
YW-2-3	10.86	209.90	423.79	0.50	0.05184	0.00241	0.13984	0.00602	0.01983	0.00038	132.9	5.4	126.6	2.4	279.7	110.2
YW-2-4	14.96	381.17	549.82	0.69	0.04842	0.00173	0.13255	0.00472	0.01988	0.00032	126.4	4.2	126.9	2.0	120.5	89.8
YW-2-5	8.68	211.88	320.94	0.66	0.04945	0.00227	0.13421	0.00605	0.01981	0.00035	127.9	5.4	126.4	2.2	168.6	107.4
YW-2-6	16.89	548.51	594.35	0.92	0.04996	0.00176	0.13687	0.00499	0.01984	0.00037	130.3	4.5	126.7	2.3	194.5	81.5
YW-2-7	13.24	349.48	435.57	0.80	0.05322	0.00286	0.15723	0.00849	0.02152	0.00039	148.3	7.4	137.3	2.5	338.9	122.2
YW-2-8	5.62	127.80	185.85	0.69	0.04973	0.00228	0.14955	0.00680	0.02183	0.00036	141.5	6.0	139.2	2.3	189.0	107.4
YW-2-9	9.16	233.37	342.05	0.68	0.04983	0.00255	0.13342	0.00650	0.01946	0.00036	127.2	5.8	124.2	2.2	187.1	118.5
YW-2-10	13.88	535.88	454.32	1.18	0.05160	0.00218	0.13944	0.00563	0.01968	0.00032	132.5	5.0	125.6	2.0	333.4	96.3
YW-2-11	5.67	107.55	216.59	0.50	0.04957	0.00227	0.13537	0.00609	0.01980	0.00031	128.9	5.4	126.4	2.0	176.0	107.4
YW-2-12	6.94	152.37	236.67	0.64	0.05059	0.00241	0.14660	0.00720	0.02094	0.00036	138.9	6.4	133.6	2.3	220.4	109.2
YW-2-13	15.62	428.52	572.49	0.75	0.04994	0.00175	0.13416	0.00445	0.01954	0.00028	127.8	4.0	124.8	1.8	190.8	81.5
YW-2-14	4.46	104.35	135.66	0.77	0.05200	0.00290	0.16005	0.00830	0.02287	0.00042	150.7	7.3	145.8	2.7	287.1	127.8
YW-2-15	12.36	280.46	452.90	0.62	0.05903	0.00251	0.16314	0.00745	0.01984	0.00034	153.5	6.5	126.6	2.2	568.6	92.6
YW-2-16	19.03	392.36	710.16	0.55	0.05008	0.00146	0.13686	0.00392	0.01988	0.00026	130.2	3.5	126.9	1.7	198.2	68.5
YW-2-17	19.03	392.36	710.16	0.55	0.05008	0.00146	0.13686	0.00392	0.01988	0.00026	130.2	3.5	126.9	1.7	198.2	68.5
YW-2-18	6.62	133.05	244.23	0.54	0.04966	0.00210	0.13709	0.00558	0.02022	0.00031	130.4	5.0	129.0	1.9	189.0	100.0
YW-2-19	13.63	341.96	502.60	0.68	0.05001	0.00189	0.13712	0.00499	0.01997	0.00030	130.5	4.5	127.5	1.9	194.5	87.0
YW-2-20	7.83	154.79	297.76	0.52	0.04874	0.00190	0.13219	0.00475	0.01990	0.00028	126.1	4.3	127.0	1.8	200.1	95.4
YW-2-21	7.36	144.03	260.86	0.55	0.04959	0.00173	0.14541	0.00545	0.02119	0.00031	137.9	4.8	135.2	1.9	176.0	76.8
YW-2-22	15.40	218.74	394.07	0.56	0.05207	0.00167	0.20804	0.00721	0.02887	0.00049	191.9	6.1	183.5	3.0	287.1	74.1
YW-2-23	4.88	104.68	179.94	0.58	0.05083	0.00233	0.13806	0.00606	0.01999	0.00032	131.3	5.4	127.6	2.0	231.6	110.2
YW-2-24	4.88	104.68	179.94	0.58	0.06212	0.00294	0.19122	0.00953	0.02236	0.00046	177.7	8.1	142.5	2.9	679.6	101.8
YW-2-25	9.74	232.10	362.16	0.64	0.04989	0.00249	0.13443	0.00667	0.01979	0.00036	128.1	6.0	126.3	2.3	190.8	112.0
YW-2-26	12.51	375.21	432.66	0.87	0.04964	0.00236	0.13601	0.00612	0.02004	0.00034	129.5	5.5	127.9	2.1	189.0	109.2
YW-2-27	13.63	358.01	495.19	0.72	0.04911	0.00271	0.13368	0.00685	0.01971	0.00035	127.4	6.1	125.8	2.2	153.8	129.6
YW-2-28	9.81	222.30	367.68	0.60	0.05028	0.00281	0.13183	0.00702	0.01943	0.00038	125.7	6.3	124.1	2.4	209.3	129.6
YW-2-29	4.42	102.19	150.52	0.68	0.05336	0.00333	0.15347	0.00977	0.02111	0.00048	145.0	8.6	134.7	3.0	342.7	140.7
YW-2-30	7.18	162.86	267.97	0.61	0.04932	0.00238	0.13271	0.00616	0.01972	0.00035	126.5	5.5	125.9	2.2	161.2	108.3
YW-2-31	8.50	213.99	315.39	0.68	0.04988	0.00259	0.13192	0.00657	0.01954	0.00039	125.8	5.9	124.8	2.4	190.8	120.4
YW-2-32	11.81	140.06	430.45	0.33	0.05164	0.00232	0.15137	0.00698	0.02128	0.00038	143.1	6.2	135.7	2.4	333.4	101.8
YW-2-33	14.65	108.41	190.93	0.57	0.06537	0.00208	0.50040	0.01781	0.05533	0.00115	412.0	12.1	347.2	7.1	787.0	68.5
YW-2-34	9.89	286.33	337.95	0.85	0.07264	0.00343	0.20030	0.00977	0.01997	0.00044	185.4	8.3	127.5	2.8	1005.6	96.3
YW-2-35	24.43	270.40	321.22	0.84	0.06159	0.00177	0.48161	0.01932	0.05626	0.00174	399.2	13.2	352.8	10.6	661.1	61.1
YW-2-36	8.79	209.57	331.46	0.63	0.04827	0.00249	0.13258	0.00673	0.01989	0.00039	126.4	6.0	126.9	2.5	122.3	109.2
YW-2-37	13.12	373.66	479.88	0.78	0.04888	0.00316	0.13590	0.00832	0.01970	0.00041	129.4	7.4	125.8	2.6	142.7	144.4
YW-2-38	12.13	295.13	439.21	0.67	0.04896	0.00238	0.13423	0.00615	0.02006	0.00038	127.9	5.5	128.0	2.4	146.4	114.8
YW-2-39	9.22	211.92	349.76	0.61	0.05032	0.00217	0.13884	0.00598	0.02003	0.00037	132.0	5.3	127.8	2.4	209.3	100.0
YW-2-40	6.12	152.16	228.53	0.67	0.04883	0.00180	0.13332	0.00470	0.01982	0.00027	127.1	4.2	126.5	1.7	139.0	91.7

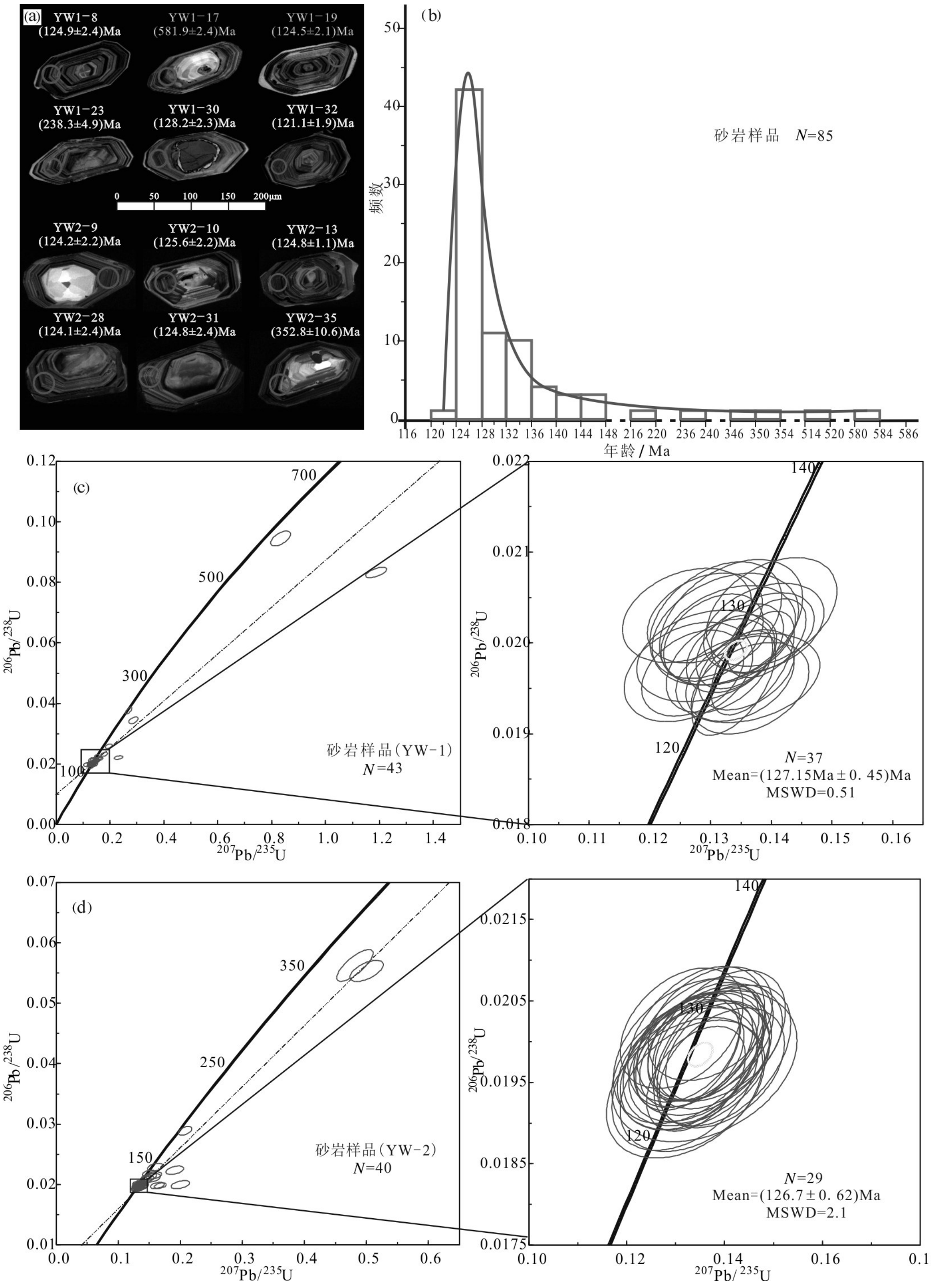

图4 杨湾组砂岩样品碎屑锆石U-Pb CL图像(a)、年龄谱图(b)以及年龄谐和图(c,d)

Fig.4 U-Pb CL image(a), histograms and probability spots if concordia ages(b) and concordia diagrams(c,d) of detrital zircon in sandstones of Yangwan Formation

层的最大沉积年代(Nelson, 2001; Dickinson and Gehrels, 2009; Tucker et al., 2013)。本文对采自杨湾组凝灰质砂岩样品进行LA-ICP-MS锆石U-Pb测年,获得最年轻单颗粒锆石年龄为121.1 Ma,表明杨湾组的沉积时代晚于121.1 Ma。依据前人在该组发现的轮藻、瓣鳃类、介形类化石(王振, 1981;

何俊德等, 1981; 张一勇等, 2000),证实杨湾组的沉积时代相当于Aptain阶,说明杨湾组的沉积时代应为早白垩世晚期,该认识与主流观点一致。

5 断裂左行走滑时代

5.1 年代学制约

本次研究区地处华南地块,杨湾组地层内的继承性锆石年龄指示沉积时代应晚于121.1 Ma,结合轮藻类化石组合指示沉积时代为早白垩世,大致相当于Aptain阶(王振,1981),同时瓣鳃类、介形类化石也指示沉积时代应为早白垩世中晚期,故而判断该期左行走滑活动应晚于121 Ma。多幅1∶5万区域地质调查表明晚白垩世早期七房村组及上覆地层未发育该期断层活动,指示该期左行走滑活动的时代上限为晚白垩世初期,进而限定了该期构造活动时间应为早白垩世末。

除皖南地区外,前人沿下扬子北东陆缘一带调查中获得类似认识,其中韩雨等(2015)、朱光等(2016)调查发现张八岭隆起带南段韧性剪切带侵位的花岗岩脉(131 Ma)叠加有左行走滑活动,导致脉岩被剪切变形。王微等(2015)进一步限定了剪切带的活动时限在129 Ma之后。韩雨等(2015)在巢湖西韦地区发现133 Ma的花岗岩因左行走滑韧性剪切变形为超糜棱岩。同期朱光等(2016)在巢湖寨山通过对晚期受韧性变形的花岗岩脉锆石U−Pb定年指示晚期左行走滑形成于124 Ma之后。此外,舒良树等(2000)通过对东南沿海一带北东向长乐—南澳大型韧性剪切带内新生白云母Ar−Ar测年获得了120~100 Ma的左旋活动年龄。

由此可见,该期活动应广泛发育于整个华南地区北东向断裂中,结合本次研究表明左行走滑的活动时限应晚于121 Ma。

5.2 区域应力场制约

自印支期扬子与华北地块碰撞、挤压,研究区中生代以来受华北陆块、华南陆块及古太平洋板块的共同影响,构造变形主要集中于板内变形。其中中三叠世—早白垩世初,区内由近SN向挤压逐渐过渡为NW−SE向挤压,本区北东向断裂表现为一系列逆冲断层,并大致以长江为界,形成南北对冲的构造格局(朱光等,1998;李三忠等,2010;Li et al., 2010;宋传中等,2014;吕庆田等,2015)。继早白垩世初期的NW−SE向挤压之后,早白垩世期间研究区应力状态为NWW−SEE向拉张,形成规模巨大的北东向正断层,并沉积有以徽州组、广德组为代表的庐枞、祁门盆地,同期侵入以碱性花岗岩为代表的中酸性岩浆岩。

进入早白垩世末期,中国东部古太平洋板块在早白垩世末发生了重大的转变,太平洋板块开始逐渐替代了伊泽奈崎板块(Maruyama et al., 1997; Cottrel and Tarduno, 2003),古地磁研究表明早白垩世末至晚白垩世初太平洋板块向北斜向俯冲(Sager, 2006; Beaman et al., 2007),推挤伊泽奈崎板块消减于西太平洋陆缘北东走向的安第斯型东亚大陆边缘岛弧之下。该期中国东部处于NNE−SSW向最大主压应力作用下(万天丰等, 2012),研究区内北东向断裂多表现为脆性高角度左行走滑断层,进而切割早白垩世岩体及红层,北东向主断裂面发育具逆冲性质的左行走滑擦痕。

之后晚白垩世区域应力场为近南北向弱拉张(朱光等, 2018),沉积有以赤山组为代表的陆相红盆。进入新生代区域最大主压应力方向分别为56~23 Ma的NWW−SEE向及23~0.78 Ma的近SN向(万天丰和赵庆乐, 2012)。

由此可见,本期构造活动与下扬子地区早白垩世末期的应力场基本一致,结合该期断裂活动野外切割早白垩世岩体及后期脉岩的证据,指示该期断裂活动应发生于早白垩世末。

5.3 白垩纪红层制约

自燕山早期华北陆块与华南陆块实现完全拼合和一体化,整个晚中生代期间共同受西太平洋板块俯冲过程、东亚大陆边缘深浅部过程的影响,其构造、岩浆、成矿、地貌演化趋势表现出一些共性(李三忠等, 2018),进而说明中国东部部分构造活动具有等时的一致性。

Zhu et al.(2012)、朱光等(2018)研究表明郯庐断裂带于早白垩世末期经历了一次重要的地质事件。该次事件导致早白垩世断陷盆地普遍经历了一次抬升、翻转与沉积间断。而由地震剖面显示,地处华北陆块的合肥盆地内下白垩统响导铺组与上白垩统张桥组之间存在着角度不整合(刘伟等, 2004),沂沭地堑内上白垩统王氏组与下白垩统大盛组之间存在角度不整合(Zhang et al., 2003),苏北

盆地内下白垩统葛村组与上白垩统浦口组之间为不整合接触(吴根耀等,2003;苗巧银等,2016)。

皖南地区地处华南陆块中东部,白垩纪以来沉积了以砂砾岩为特征的陆相红盆,沉积相分析表明地层内部存在多个沉积间断面,地层接触关系为平行或角度不整合(吴跃东等,2003)。早、晚白垩世之交经历了由压扭性构造体制向伸展构造体制转换,即所谓的黄桥事件(张永鸿,1991;张沛等,2009;田朋飞等,2012;何将启等, 2014)。该事件导致晚白垩世地层沉积前发生大面积剥蚀、夷平作用,形成了皖南地区诸如晚白垩世初七房村组与下伏早白垩世杨湾组之间的角度不整合接触,说明该期陆相盆地在演化过程中存在抬升和剥蚀。此外磷灰石裂变径迹(AFT)实验证实导致上述不整合接触的黄桥事件终止于110 Ma左右(张沛等,2009;刘文浩等, 2012;王丹萍等, 2014),说明受制于压扭性构造体制的左行走滑活动的上限为110 Ma左右。

综上可知,皖南地区北东向断裂左行走滑的活动时限为121~110 Ma,是区域性NNE-SSW向挤压作用下的活动产物。

6　构造背景讨论

中国东部自侏罗纪开始就一直受板块俯冲作用影响,伊泽奈崎板块和太平洋板块俯冲在很大程度上控制了中国东部中生代岩浆活动和盆地演化(Faure et al., 2008)。

从中侏罗世开始中国东部发生大规模的岩浆活动,时限横跨于173~70 Ma(周涛发等, 2004; 许文良等, 2004,2013;邢光福等, 2009,2017; 毛建仁等, 2014)。其中华南地区在燕山中晚期的拉张环境下产出有大量A型花岗岩,年代学资料显示存在139~123 Ma和100~70 Ma两个阶段(王强等, 2005;Wu et al., 2005;袁峰等,2006;Sun et al., 2007;范裕等, 2008;Wong et al., 2009;张旗等, 2009),前者广泛分布于整个中国东部,诸如下扬子带、苏鲁带、山海关带和碾子山带,后者主要分布于东南沿海的闽浙带(李三忠等,2018),区域上年龄还具自北西向南东逐渐变新的特点。对于该类花岗岩形成于伸展背景的观点已基本统一,且指示与岩石圈减薄有关(吴福元等,2003;牛耀龄,2005;董树文等,2007)。但上述两期A型花岗岩之间存在有122~110 Ma岩浆活动的宁静期或称明显的间歇期(Li X H, 2000; Sun et al., 2007; 孙卫东等, 2008),说明两期拉张环境之间存在一次短暂的挤压环境。

中国东部早晚白垩世陆相红层之间角度不整合证据指示盆地形成期间发生过沉积间断、隆升剥蚀的过程,即存在构造应力场的转变,发生拉张—挤压—再拉张的过程,这一特征与中国东部岩浆岩的演化过程是近乎一致的。朱光(2016)分析证实华北克拉通峰值破坏的中止发生在早白垩世末,是区域性的伸展转变为挤压导致的,进而认为区域性挤压事件是中国东部早白垩世末经历了一次重要的地质事件,具体表现为早白垩世末普遍经历了一次抬升、翻转与沉积间断(Zhu et al., 2012; 董树文等, 2019)。由此可见皖南地区北东向断裂的左行走滑与华北克拉通峰值破坏的中止具有一定的等时性,均与早白垩世末期的构造事件有关,或都为早白垩世末期中国东部构造表现的不同形式而已。

与此同时,胶东、五河地区典型的石英脉金矿的形成时代的峰值集中于110 Ma(吕承训等, 2017)。该类型的矿床通常形成于挤压环境,且时限很短(Cox et al., 2004)。对于该类金矿的成矿机制也印证了该期中国东部存在一期构造事件,即记录了中国东部在此期间由拉张向挤压转变的过程。

综上可知,地层、构造、岩浆岩证据均表明皖南地区乃至中国东部早、晚白垩世之交发生过一期重要的地质事件,部分学者将其称为黄桥事件。对比中国东部的构造演化史及与同期伊泽奈崎板块和太平洋板块的活动轨迹后发现,两者在时限上具有相当的一致性。其中太平洋板块在该期(125~110 Ma)向北西发生俯冲挤压,其影响机制无法造成中国东部北东向断裂的走滑活动。李三忠等(2018)对中生代板块俯冲的研究表明太平洋板块对东亚陆缘的直接作用最早应在110 Ma之后,而Engebretson et al.(1985)针对伊泽奈崎板块的古地磁研究也表明太平洋板块俯冲作用最早也在晚白垩世之后,故此时中国东部仍处于伊泽奈崎板块的直接作用下。Kadarusman et al.(2004)通过板块重建认为受洋中脊的扩张作用影响,早白垩世晚期伊泽奈崎板块表现为以2倍速率向NNE向俯冲消减于北东向的东亚陆缘岛弧之下,进而引发中国东部大规模的走滑拉分。此后110 Ma以来或新生代东

亚陆缘块体运动，才可能与太平洋板块的运动方向具有可对比性（Zhu et al., 2015; Huang et al., 2015）。

由此可知，造成皖南地区乃至中国东部早白垩世末期北东向断裂的左行走滑活动与伊泽奈崎板块对华南地块的挤压作用关系密切。

7 结 论

（1）依据杨湾组碎屑锆石谱和年龄指示其物源可能部分来自于早白垩世中期岩浆岩。而由最年轻锆石年龄指示其沉积时代应晚于121.1 Ma，结合前人瓣鳃类、介形类化石证据，推测时代大致位于早白垩世晚期。

（2）皖南地区北东向断裂在早白垩世末期（121～110 Ma）发生的走滑挤压构造，形成高角度的左行平移断层，是NNE−SSW向挤压作用的产物，可能与伊泽奈崎板块对中国东部的挤压作用有关。

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