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江南造山带东段新元古代至早中生代多期造山作用特征

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提要:新元古代江南造山带远离晚中生代活动大陆边缘,是研究华南地区新元古代至早中生代多期造山作用的理想对象。文章通过对江南造山带东段沉积建造、岩浆活动、构造变形以及同位素年代学数据的综合分析,总结了其晋宁期、广西期以及印支期造山作用的特征。江南造山带东段在晋宁期经历了南北两侧大洋俯冲和两期碰撞造山作用。新元古代早期(880~860 Ma)双溪坞岛弧与扬子陆块东南缘发生弧-陆碰撞作用,形成淡色花岗岩、高压蓝片岩、NNE向褶皱-逆冲构造以及弧后前陆盆地。新元古代中期(约850 Ma),扬子陆块北缘开始发育由北向南的大洋俯冲。随着俯冲作用的进行,弧后盆地发生关闭,扬子陆块与华夏陆块发生陆-陆碰撞并形成新元古代(820~810 Ma)江南造山带,导致近E-W走向褶皱-逆冲构造、韧性变形以及过铝质花岗岩的发育。江南造山带东段在约810 Ma开始发生后造山垮塌和裂谷作用,以发育南华纪早期(805~750 Ma)花岗岩、中酸性火山岩、基性岩以及裂谷盆地为特征。江南造山带东段万载—南昌—景德镇—歙县断裂带以南地区卷入了华南广西期造山作用,发育近E-W走向由南向北的逆冲构造(465~450 Ma)、NNE向正花状构造 (449~430 Ma) 以及后造山近E-W走向韧性走滑剪切带(429~380 Ma)。印支期造山作用导致了NNE向褶皱-逆冲构造和花岗岩的发育,并奠定了江南造山带东段的基本构造面貌。

关 键 词:造山作用;沉积建造;岩浆作用;构造变形;年代学;江南造山带东段

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Characteristics of Neoproterozoic—Early Mesozoic multiphase orogenic activities of eastern Jiangnan Orogen

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Abstract: The Jiangnan Orogen is a suitable region for deciphering Neoproterozoic to Early Mesozoic multiphase orogenic

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activities of the South China Block because it is far away from the Late Mesozoic active continental margin. Based on a comprehensive analysis of such factors as deposition, magmatism, structural deformation and geochronology, the authors summarized the features of Neoproterozoic, Early Paleozoic and Early Mesozoic orogenies in the eastern Jiangnan Orogen. The eastern Jiangnan Orogen underwent southern and northern subductions as well as two stages of collisions in Neoproterozoic. In 880−860 Ma of the early Neoproterozoic period, arc−continent collision between the Shuangxiwu island arc and the southeastern margin of Yangtze Block induced the formation of 880−860 Ma light granites, high−pressure blueschist, NNE−striking fold−and−thrust structures and retro−arc foreland basins. Southward subduction along the northern margin of Yangtze Block commenced at about 850 Ma. This subduction resulted in the closure of back−arc basin and final collision between the Yangtze and Cathaysia blocks, and triggered nearly EW− striking fold− and− thrust structures, ductile deformation and peraluminous granodiorites in the eastern Jiangnan Orogen. The eastern Jiangnan Orogen started to collapse and rift at about 810 Ma, and produced 805−750 Ma granites, felsic volcanic rocks, mafic dikes and rift basins. Early Paleozoic orogeny occurred in the southern area of the Wanzai−Nanchang−Jingdezhen−Shexian fault zone within the Jiangnan Orogen. This orogeny led to the formation of nearly EW−striking top−to−the north thrusting, NNE−striking positive flower structures and post−orogenic nearly EW−striking dextral shear zones. The Early Mesozoic orogeny brought about NNE−striking fold and thrust structures and granites, which established the basic features of the present eastern Jiangnan Orogen.

Key words: orogeny; deposition; magmatism; structural deformation; geochronology; eastern Jiangnan Orogen

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1 引 言

江南造山带是新元古代扬子与华夏陆块碰撞拼合的产物，呈向NW凸出的弧形带状展布，延伸长度超过1500 km，出露宽度可达120 km[1−8]。自卢华复等于1975年[9]正式发文引用板块学说解释江南造山带的构造演化以来，其研究历史已近40年。特别近10年以来随着Rodinia超大陆聚合和裂解相关研究的兴起，江南造山带的研究取得了突破性进展：(1)地质和地球物理资料表明江南造山带南北边界分别为江山—绍兴断裂带和江南断裂带[4,7,10−12]；(2)江南造山带主体由新元古代中期(840~820 Ma)浊积岩和花岗闪长岩组成[7,13−21]；(3)江南造山带经历了新元古代碰撞造山作用和后造山伸展—裂谷作用[1,2,4−6,18,19,22−26]。随着研究的深入，关于江南造山带的争论也越来越多，主要集中在：(1)江南造山带的形成时代及其动力学机制[2−8,18−20]；(2)江南造山带多期造山作用特征及其形成时代[5,27−32]；(3)江南造山带对广西运动和印支运动的构造响应[8,32−39]。

本文的研究区江南造山带东段是指由南侧江山—绍兴断裂带[40]、北侧江南断裂带[41]以及东侧赣东北断裂带[36]围限的皖南—赣北地区(图1)。本文在全面回顾前人研究的基础之上，结合笔者最近几年的区域地质调查和研究工作，对新元古代至早中生代的沉积过程、岩浆作用、构造变形以及同位素年代学进行了综合分析，总结了江南造山带东段晋宁期、广西期以及印支期造山作用的特征。

2 沉积建造

江南造山带东段出露的地层以青白口系浊积岩为主，在皖南和赣西北局部地区可见南华纪至早古生代的连续沉积(图1)。晚古生代以海相沉积为主，主要展布在NEE向万载—南昌—景德镇—歙县断裂带以南的九岭南缘地区。中生代以侏罗纪和白垩纪陆相碎屑沉积为主，主要发育于江南造山带东段中生代上叠盆地之中。

2.1 青白口系

江南造山带东段青白口系主要是新元古代中期巨厚的以泥砂质岩为主夹少量火山岩的沉积建造。该套岩石由北至南分别命名为庐山垄群、星子岩群、双桥山群、溪口岩群以及万年群(图2)。庐山垄群和星子岩群主要分布在庐山地区，两者以晚中生代拆离断层相接触。

庐山垄群下部筲箕洼组为一套海相喷溢细碧岩−角斑岩−变石英角斑岩夹粉砂岩组合，上部汉阳峰组为一套陆相火山−沉积作用形成的火山碎屑岩和喷出岩[42]。地球化学指示筲箕洼组火山岩形成于岛弧或弧后盆地环境[43,44]。星子岩群主体为石榴石

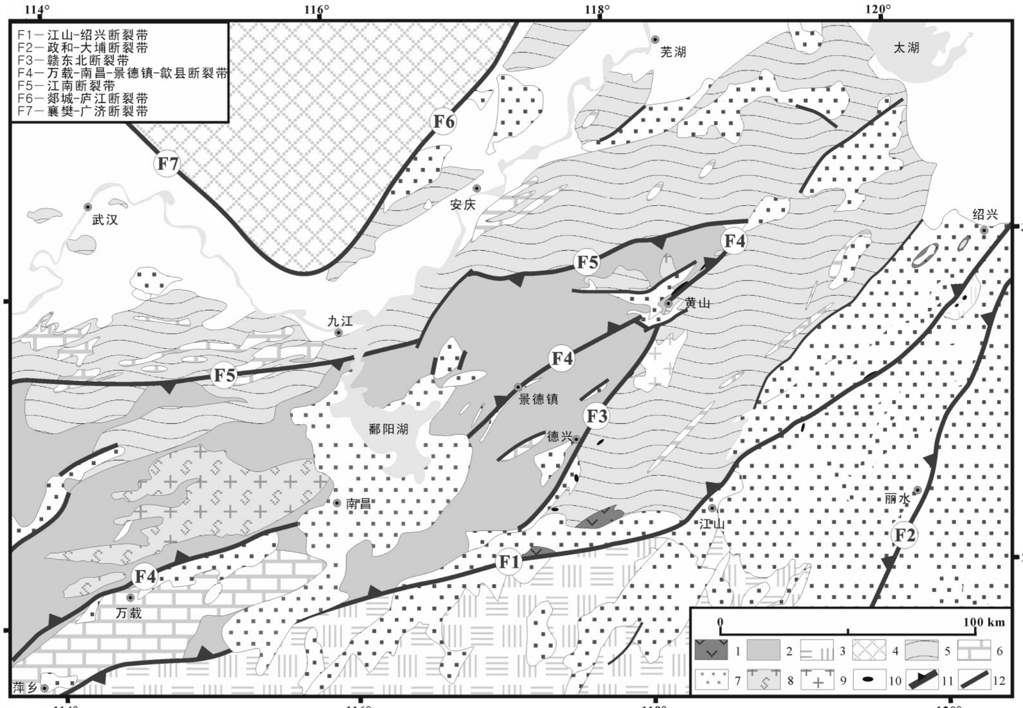

图1 江南造山带东段地质简图

1—中元古代末—新元古代初期地层；2—新元古代江南造山带；3—早古生代武夷造山带；4—早中生代大别造山带；5—南华纪至志留纪地层；6—上古生界；7—中新生代盆地；8—青白口纪花岗岩；9—南华纪花岗岩；10—蛇绿岩；11—主边界断层；12—断裂

Fig.1 Sketch geological map of the eastern Jiangnan Orogen

1−Late Mesoroterozoic to earliest Neoproterozoic sequences; 2−Neoproterozoic Jiangnan Orogen; 3−Early Paleozoic Wuyishan Orogen; 4−Early Mesozoic Dabieshan Orogen; 5−Nanhua−Silurian sequences; 6−Upper Paleozoic; 7−Mesozoic−Cenozoic basins; 8−830−820 Ma granites; 9− 800−780 Ma granites; 10 −Neoproterozoic ophiolite; 11−Boundary fault; 12−Faults

片岩、云母石英片岩、千枚岩以及少量斜长角闪岩，其原岩以泥砂岩为主，夹少量硅质岩、基性火山岩以及碳酸盐岩[45]。星子岩群普遍发育中高级变质作用，是晚中生代构造变形与岩浆热动力变质的共同结果[46,47]。双桥山群主体由云母片岩、千枚岩、板岩以及变质砂岩组成，为一套厚度巨大的以泥砂质岩石为主夹少量火山岩的复理石建造，形成于浅海陆棚−深海环境[48]。溪口岩群是由板岩、千枚岩以及变质砂岩组成的复理石建造，形成于滨浅海—深海环境[49]❶。双桥山群和溪口岩群以NEE向万载—南昌—景德镇—歙县断裂带为界，总体变质程度较低，局部可见保存完好的原始沉积构造[48]❶。万年群下部为以滨海相火山碎屑岩为主的含砾碎屑岩建造，上部为海相泥砂质碎屑岩沉积为主夹火山碎屑岩和熔岩的复理石建造[50]。根据现有的高精度同位素年代学数据（表1），庐山垄群、星子岩群、双桥山群、溪口岩群以及万年群均形成于青白口纪末期（840~820 Ma）。

江南造山带东段赣东北地区还出露了少量新元古代早期沉积，以泥砂质岩石为主夹少量火山岩。层间凝灰岩和石英角斑岩指示其形成于约880 Ma，可能形成于弧后前陆盆地环境[3]。

2.2 南华系—志留系

江南造山带东段南华—志留系主要为浅海相沉积，其以角度不整合覆盖在下伏青白口系之上（图3）。赣西北地区南华纪早期火山−沉积岩由下部马涧桥组和上部硐门组构成，沉积厚度超过420 m。马涧桥组为一套紫红色安山质沉凝灰岩夹英安岩组合，底部为火山角砾岩；硐门组下部为灰白色含砾砂岩与长石石英砂岩互层，上部为灰黑色岩屑砂岩、粉砂岩以及页岩组成韵律互层。皖南地区同期火山−沉积岩由历口群和休宁组组成，沉积厚度

❶徐先兵，陈能松，章泽军，等. 江西省1∶5万清华、江湾幅区域地质调查报告[R]. 武汉：中国地质大学（武汉）地质调查研究院，2014.

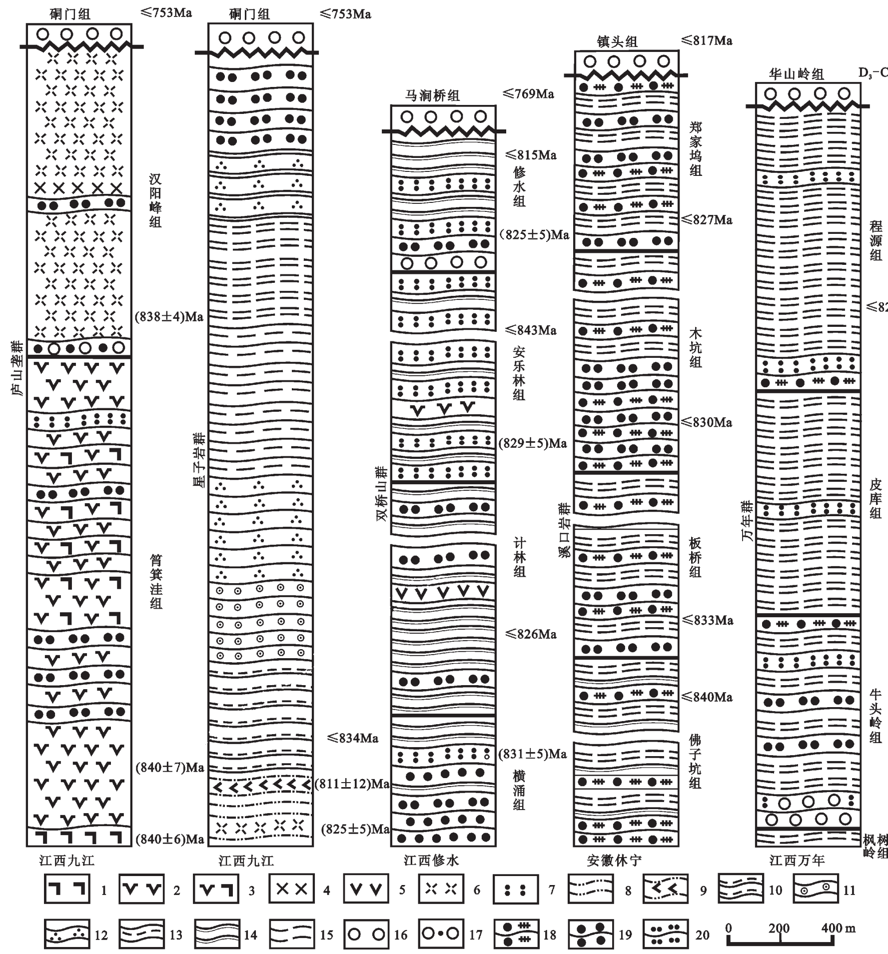

图2 江南造山带东段新元古代中期地层柱状图

1—细碧岩;2—角斑岩;3—细碧—角斑岩;4—安山岩;5—英安岩;6—流纹岩;7—凝灰岩;8—混合岩;9—斜长角闪岩;10—片麻岩;11—变粒岩;12—石英片岩;13—云母片岩;14—板岩;15—千枚岩;16—变砾岩;17—变砂砾岩;18—变岩屑砂岩;19—变砂岩;20—变粉砂岩

Fig.2 Histogram of Middle Neoproterozoic sequences in the eastern Jiangnan Orogen

1-Spilite; 2-Keratophyre; 3-Spilite- keratophyre; 4-Andesite; 5-Dacite; 6-Rhyolite; 7-Tuff; 8- Migmatite; 9-Amphibolites; 10-Gneiss; 11-Leptynite; 12-Quartz schist; 13- Mica schist; 14-Slate; 15-Phyllite; 16-Meta-conglomerate; 17-Meta-sandy conglomerate; 18- Meta-lithic sandstones; 19-Meta-sandstone; 20-Meta-siltstone

约1600 m。历口群下部邓家组由石英砂岩、粉砂岩和板岩组成,上部铺岭组由安山岩和安山质凝灰岩组成;休宁组不整合覆盖于铺岭组之上,主体为砂岩、粉砂岩以及泥岩组成韵律,底部为紫红色砾岩。皖—浙—赣交界地区南华纪早期火山-沉积岩由井潭组和休宁组构成,沉积厚度达到2100 m。井潭组下部为灰绿色千枚岩、流纹岩以及凝灰岩,上部以安山岩为主夹流纹岩和凝灰岩。浙北地区同期火山-沉积岩由河上镇群和志棠组组成,沉积厚度超过4300 m。河上镇群自下而上可以划分为骆家门组、虹赤村组以及上墅组。骆家门组下部为砾岩和砂砾岩,上部为泥砂岩;虹赤村组以岩屑砂岩为主夹少量火山岩;上墅组下部以安山玄武岩为主,上部以流纹岩为主,构成双峰式火山岩组合。志棠组主要由砾岩、砂砾岩、凝灰质粉砂岩、细砂岩、凝灰岩、粉砂岩、粉砂质页岩组成,不整合覆盖在上墅组之上。

在新元古代雪球事件的影响下,江南造山带东段及邻区发育良好的冰碛岩,称之为南沱组或雷公坞组。南沱组为灰绿、紫褐色冰碛泥砾岩;雷公坞组主要由灰绿色冰碛泥砾岩、含锰白云岩、黑色页岩构成。现在普遍认为雷公坞组是华南古城冰期和南沱冰期联合作用的产物,对应于全球雪球事件中的司图特冰期(718~660 Ma)和马林诺冰期(651~635 Ma)[51-55]。随

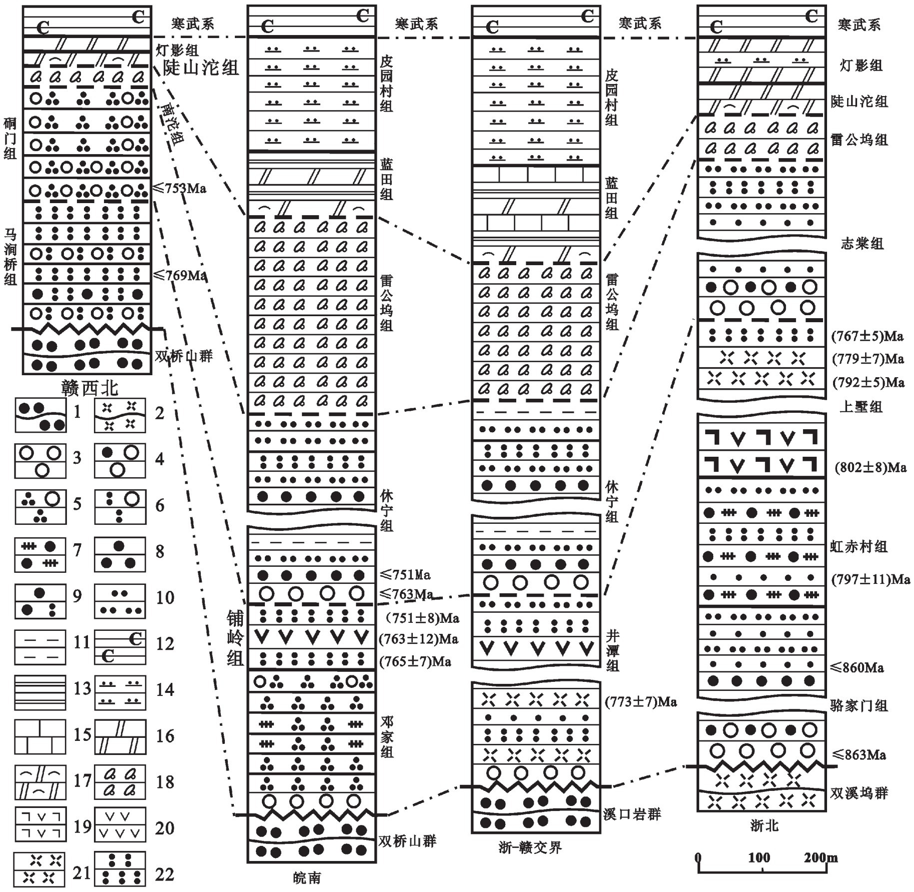

图3 江南造山带东段南华纪地层柱状图

1—变质砂岩;2—变流纹岩;3—砾岩;4—砂砾岩;5—含砾石英砂岩;6—含砾凝灰岩;7—岩屑砂岩;8—砂岩;9—凝灰质砂岩;10—粉砂岩;11—泥岩;12—炭质板岩;13—页岩;14,硅质岩;15—灰岩;16—白云岩;17—含锰白云岩;18—冰碛岩;19—安山玄武岩;20—安山岩;21—流纹岩;22—凝灰岩

Fig.3 Histogram of Nanhua period sequences in the eastern Jiangnan Orogen

1−Meta−sandstone; 2−Meta−rhyolite; 3−Conglomerate; 4−Sandy conglomerate; 5−Pebbly quartz sandstone; 6−Pebbly tuff; 7−Lithic sandstone; 8−Sandstone; 9−Tuffaceous sandstone; 10−Siltstone; 11−Mudstone; 12−Carbonaceous slate; 13−Shale; 14−Chert; 15− Limestone; 16−Dolomite; 17− Manganese dolomite; 18−Moraine rock; 19−Andesitic basalt; 20− Andesite; 21−Rhyolite; 22−Tuff

着新元古代冰川融化,江南造山带周缘水体加深,并接受白云岩和硅质岩等深水沉积。

江南造山带东段下古生界主要出露在赣西北和皖南地区,造山带核部未见出露,与下伏南华纪地层呈整合接触。赣西北早古生代地层主要由寒武纪至志留纪炭质页岩、泥灰岩、条带状灰岩以及瘤状灰岩组成,其厚度超过4600 m,形成于滨岸斜坡环境。皖南地区早古生代地层主要出露于黟县和歙县地区,由寒武纪至志留纪炭质页岩、泥灰岩以及粉砂岩组成,其总厚超过4 km,形成于滨岸—陆架环境。

2.3 上泥盆统至上三叠统

江南造山带东段晚泥盆—早三叠世地层主体为石炭—二叠纪深海相碳酸盐和硅质岩组成,其底部为晚泥盆世石英质砾岩、砂砾岩和石英砂岩,其顶部为早三叠世石英砂岩、粉砂岩以及泥岩。该套地层主要出露于北东向万载—南昌—景德镇—歙县断裂带以南的九岭南缘地区,在造山带核部主要残留于断裂带之中。江南造山带东段晚泥盆—早三叠世地层被晚三叠世—中侏罗世陆相碎屑岩角度不整合覆盖。

3 岩浆活动

江南造山带东段最早的岩浆记录为中—新元古代蛇绿岩,出露于赣东北弋阳—德兴地区,主体岩性为蛇纹石化橄榄岩、辉长岩、细碧−角斑岩以及

硅质岩等[56]，地球化学指示其形成于岛弧环境[57,58]。15个蛇绿岩样品拟合的Sm−Nd等时线年龄为(955±44) Ma，与蛇绿岩中高度分异的岩浆结晶年龄(约970 Ma)在误差范围内近一致[59,60]，指示江南造山带东段新元古代板块俯冲开始于约1.0 Ga。

江南造山带东段新元古代早期基性岩浆广泛发育[24,61−66]，指示其在860~840 Ma发生强烈的裂解作用，与华夏陆块的大陆裂解时限基本一致[67]。稍后的岛弧型火山岩活动主要发育于江南造山带北缘，其形成时代为850~830 Ma，以赣北庐山垄群为代表[43,44,68]。同期弧后盆地的强烈扩张导致皖南伏川蛇绿岩的发育，其主要由地幔橄榄岩、堆晶岩、枕状熔岩以及少量硅质岩组成[56]，形成时代为827~819 Ma[69,70]。

新元古代中期过铝质花岗岩广泛发育于江南造山带核部，形成大面积花岗杂岩，以九岭杂岩、休宁岩体、许村岩体以及歙县岩体为代表，岩性主体为含堇青石黑云母花岗闪长岩，形成时代为828~819 Ma，为新元古代中期碰撞造山作用中沉积物部分熔融的产物[13,14,71−73]。

江南造山带东段新元古代中期基性岩浆广泛发育[3,25,74−76]，指示其在805~785 Ma发生强烈的伸展作用，并发育同期后造山伸展盆地[19]。同期火山岩主要发育于造山带的边缘，包括东南缘上墅组、井潭组、桃源组以及北缘铺岭组和马涧桥组，以中酸性流纹岩、英安岩以及凝灰岩为主，偶夹玄武岩。中酸性火山岩在形成时代表现为东南早、西北晚，东南缘形成于800~770 Ma[24−26,77,78]，西北缘形成于765~750 Ma[25]。同期花岗质岩浆活动形成了石耳山杂岩和道林山杂岩，形成时代为794~771 Ma[24,26,79]❶，为后造山伸展或裂谷作用的产物[26,80]。

现有资料表明江南造山带东段早古生代和早中生代岩浆活动不发育，仅九岭南缘地区有三叠纪蒙山岩体的报道，其主体岩性为黑云母花岗岩，形成时代236~217 Ma[39,81]。

4　变形变质

江南造山带自新元古代形成以来，经历了长期构造演化和多期造山作用，构造变形强烈且复杂，其变形样式和形成时代一直是地质学家们争论的焦点。

新元古代早期(880~860 Ma)，沿江南造山带东段东南缘NNE向弋阳—德兴断裂带发育了强烈的碰撞作用，形成了高压蓝片岩、糜棱岩化闪长岩以及淡色花岗岩[1,23,35]。另外，在赣东北地区新元古代早期(约880 Ma)弧后前陆盆地中识别出近N−S向褶皱变形[3,30]，与上述NNE向构造线方向基本一致。

江南造山带东段新元古代中期(840~820 Ma)浊积岩发育强烈的褶皱变形，形成近E−W向障公山复背斜和九岭复背斜。笔者通过对皖浙赣交界地区1∶5万区域地质调查发现(图4)，近E−W向褶皱以平卧褶皱、同斜倒转褶皱以及倾竖褶皱为主❶。系统的褶皱枢纽测量表明，近E−W向褶皱枢纽倾向E或W，倾角为2°~85°[32]。同期褶皱在赣东北田畈街地区表现为近E−W向同斜紧闭褶皱，并叠加在早期近N−S向褶皱之上[30]。同期逆冲推覆变形相对较弱，主要表现为顺层或小角度切层的由北向南逆冲，并导致歙县伏川蛇绿岩带构造侵位于歙县花岗闪长岩之上[82]。同期韧性变形主要记录在NNE向东乡—歙县剪切带中，表现为左旋走滑剪切，$^{40}Ar/^{39}Ar$年龄指示其形成于800~770 Ma[49,83]。

江南造山带东段广西期构造变形以近E−W走向的北向逆冲构造、NNE向正花状构造以及近E−W向右旋韧性剪切带为特征[32]。近E−W走向逆冲构造主要表现为由南向北的韧性逆冲作用[32,39,49]。江南造山带东段南缘边界江山—绍兴断裂带中发育由南向北逆冲，并导致混合岩化，其形成时代为433~421 Ma[64,84,85,86]。另外，江南造山带核部九岭和障公山南缘地区均发育由南向北的韧性逆冲作用，$^{40}Ar/^{39}Ar$年代学指示逆冲作用形成于465~450 Ma[32,39]。广西期NNE向正花状构造由江湾右旋韧性剪切带、北北东向褶皱以及逆冲构造组成(图4)，$^{40}Ar/^{39}Ar$年代学指示其形成于449~430 Ma[32,39,87]。近E−W走向由南向北的逆冲构造和NNE向正花状构造均形成于早古生代，指示江南造山带早古生代发生了构造应力场转换或江南造山带东段广西期构造变形受近E−W向江山—绍兴断裂和NNE向赣东北断裂的制约。早古生代末期，江南造山带核部还发育近E−W走向右旋剪切带，$^{40}Ar/^{39}Ar$年代学指示其形成于429~380 Ma[32,39,88]。

区域地质调查表明江南造山带东段印支期构

❶徐先兵，陈能松，章泽军，等. 江西省1∶5万清华、江湾幅区域地质调查报告[R]. 武汉：中国地质大学(武汉)地质调查研究院，2014.

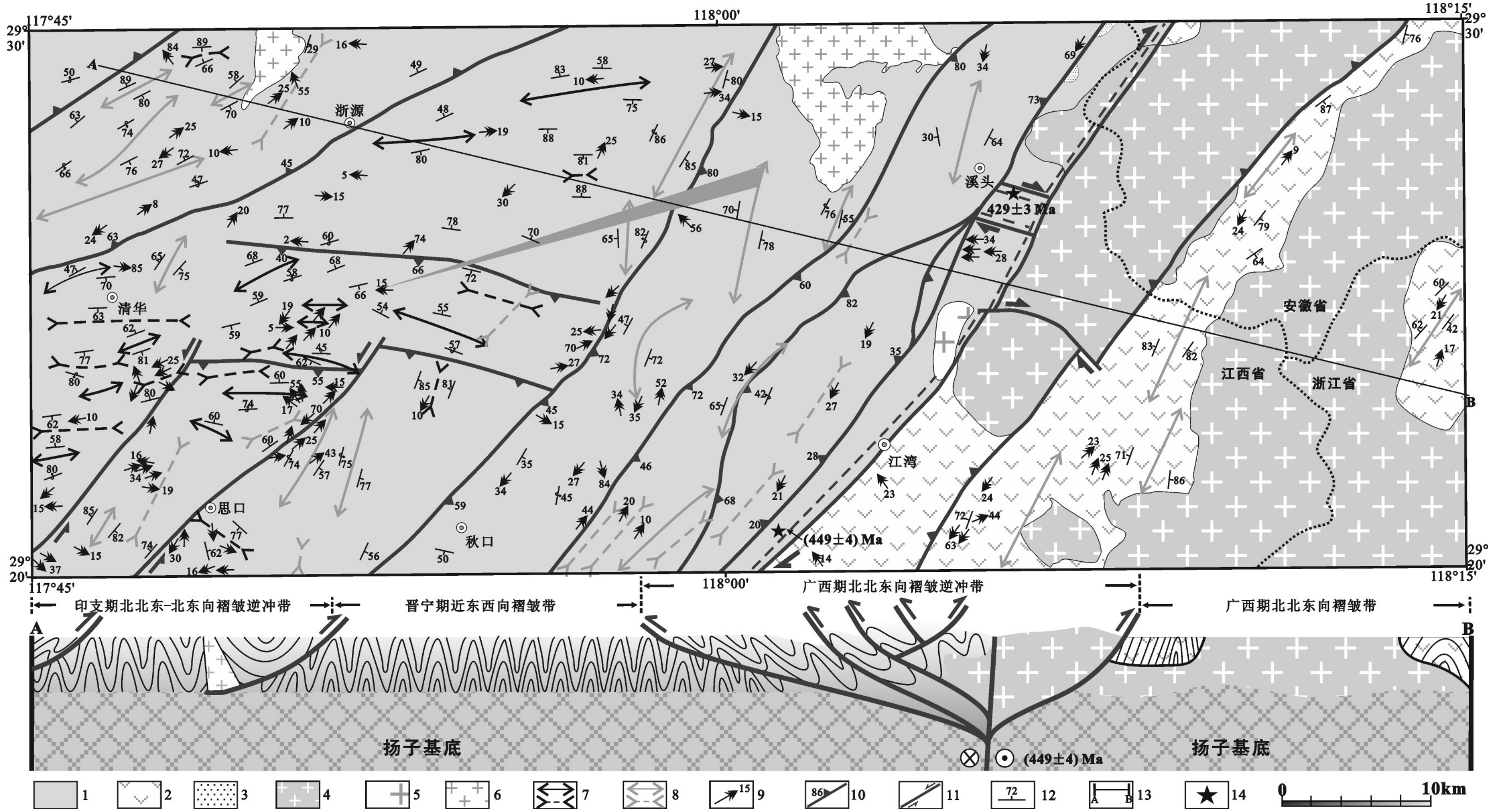

图4 皖浙赣交界清华与江湾地区构造纲要图

1—溪口岩群；2—河上镇群；3—侏罗系；4—南华纪花岗岩；5—晚侏罗世花岗岩；6—早白垩世花岗岩；7—晋宁期褶皱；8—广西期褶皱；9—褶皱枢纽及倾伏角；10—逆冲断裂；11—走滑断裂；12—产状；13—图切剖面；14—氩氩年龄采样点

Fig.4 Structural outline map of Qinghua and Jiangwan area in Anhui−Zhejiang−Jiangxi border region

1−Xikou Group; 2−Heshangzhen Group; 3−Jurassic; 4−800~780 Ma granite; 5−Late Jurassic granite; 6−Early Cretaceous granite; 7−Neoproterozoic folds; 8−Early Paleozoic folds; 9−Fold hinge and its plunging angle;10−Thrust; 11−Strike−slip fault; 12−Attitude; 13−Cross section; 14−Sampling location

表1 江南造山带东段新元古代至早中生代同位素年龄数据一览

Table 1 List of Neoproterozoic to Early Mesozoic isotope ages in eastern Jiangnan Orogen

岩石单元	地理位置	岩石定名	年龄/ Ma	测试方法	数据来源
中元古代晚期被动大陆边缘沉积					
铁砂街群	江西弋阳	变流纹岩	1159±8	SHRIMP 锆石 U-Pb	[90]
	江西弋阳	变流纹岩	1172±10	SHRIMP 锆石 U-Pb	[89]
	江西弋阳	变流纹岩	1143±9	SHRIMP 锆石 U-Pb	[89]
	江西弋阳	变流纹岩	1140±7	SHRIMP 锆石 U-Pb	[89]
	江西弋阳	变流纹岩	1132±8	SHRIMP 锆石 U-Pb	[89]
田里片岩	江西广丰	云母石英片岩	≤1535	SHRIMP 锆石 U-Pb	[5]
	江西广丰	云母石英片岩	1015±4	白云母 $^{40}Ar/^{39}Ar$	[5]
	江西广丰	云母石英片岩	968±4	白云母 $^{40}Ar/^{39}Ar$	[5]
	江西广丰	云母石英片岩	1019±30	白云母 $^{40}Ar/^{39}Ar$	[88]
新元古代早期岛弧型蛇绿岩					
弋阳—德兴蛇绿混杂岩带	江西弋阳	蛇绿岩套	955±44	Sm-Nd 等时线	[59]
	江西德兴	西湾钠长花岗岩	968±23	SHRIMP 锆石 U-Pb	[59]
	江西德兴	西湾斜长花岗岩	970±21	SHRIMP 锆石 U-Pb	[60]
新元古代早期岛弧型岩浆活动					
双溪坞群火山岩	浙江绍兴	平水组细碧岩	978±44	Sm-Nd 等时线	[59]
	浙江绍兴	平水组角斑岩	965±12	LA-ICP-MS 锆石 U-Pb	[6]
	浙江富阳	北坞组流纹岩	926±15	SHRIMP 锆石 U-Pb	[6]
	浙江富阳	章村组流纹岩	891±12	SHRIMP 锆石 U-Pb	[6]
侵入岩	浙江绍兴	桃红英云闪长岩	913±15	SHRIMP 锆石 U-Pb	[92]
	浙江绍兴	西裘花岗闪长岩	905±14	SHRIMP 锆石 U-Pb	[92]
	浙江绍兴	平水闪长岩	932±7	LA-ICP-MS 锆石 U-Pb	[93]
	浙江绍兴	平水玄武玢岩脉	916±6	LA-ICP-MS 锆石 U-Pb	[93]
	浙江绍兴	平水斜长花岗岩	902±5	LA-ICP-MS 锆石 U-Pb	[93]
新元古代早期变形变质					
NNE 向弋阳—德兴断裂带	江西德兴	淡色花岗岩/逆冲	880±19	SHRIMP 锆石 U-Pb	[23]
	江西德兴	蓝片岩/逆冲	866±14	蓝闪石 K-Ar 法	[1]
	江西德兴	糜棱化闪长岩/逆冲	857±18	角闪石 $^{40}Ar/^{39}Ar$	[35]
新元古代早期中-基性岩浆活动					
中-基性岩浆活动	湖南浏阳	玄武岩	860±20	SHRIMP 锆石 U-Pb	[66]
	浙江富阳	辉绿岩墙	849±7	SHRIMP 锆石 U-Pb	[24]
	江西横峰	石英正长岩	848±4	SIMS 锆石 U-Pb	[65]
	安徽歙县	辉长岩	848±12	SHRIMP 锆石 U-Pb	[62]
	江西宜丰	辉绿岩	847±18	LA-ICP-MS 锆石 U-Pb	[66]
	浙江诸暨	角闪辉石岩	844±3	LA-ICP-MS 锆石 U-Pb	[63]
	浙江诸暨	辉长-闪长岩	841±6	SHRIMP 锆石 U-Pb	[64]
	江西德兴	辉绿岩	839±5	LA-ICP-MS 锆石 U-Pb	[61]
	湖南浏阳	玄武岩	838±12	SIMS 锆石 U-Pb	[66]
新元古代中期弧后盆地沉积					
庐山垄群	江西庐山	筲箕洼组英安岩	840±7	SHRIMP 锆石 U-Pb	[43]
	江西庐山	筲箕洼组细碧岩	840±6	SHRIMP 锆石 U-Pb	[111]

续表1

岩石单元	地理位置	岩石定名	年龄/Ma	测试方法	数据来源
庐山垄群	江西庐山	筲箕洼组流纹岩	833±4	SHRIMP 锆石 U-Pb	[111]
	江西庐山	筲箕洼组流纹岩	831±3	SHRIMP 锆石 U-Pb	[111]
	江西庐山	筲箕洼组流纹岩	828±6	SHRIMP 锆石 U-Pb	[44]
	江西庐山	汉阳峰组流纹岩	838±4	SHRIMP 锆石 U-Pb	[66]
	江西庐山	汉阳峰组流纹岩	852±4	LA-ICP-MS 锆石 U-Pb	[66]
星子岩群	江西庐山	角闪岩	811±12	SHRIMP 锆石 U-Pb	[44]
	江西庐山	变流纹岩	825±5	SHRIMP 锆石 U-Pb	[111]
	江西庐山	钠长变粒岩	≤851	SHRIMP 锆石 U-Pb	[43]
双桥山群	江西修水	修水组凝灰岩	825±5	SHRIMP 锆石 U-Pb	[16]
	江西修水	修水组砂岩	≤815	LA-ICP-MS 锆石 U-Pb	[18]
	安徽祁门	安乐林组凝灰岩	829±5	SHRIMP 锆石 U-Pb	[15]
	江西修水	安乐林组砂岩	≤843	LA-ICP-MS 锆石 U-Pb	[18]
	江西修水	计林组砂岩	≤826	LA-ICP-MS 锆石 U-Pb	[18]
	江西浮梁	横涌组凝灰岩	831±5	SHRIMP 锆石 U-Pb	[15]
	安徽祁门	凝灰岩	825±7	SHRIMP 锆石 U-Pb	[21]
	安徽祁门	变安山岩	822±6	LA-ICP-MS 锆石 U-Pb	[17]
	安徽祁门	变流纹岩	821±4	LA-ICP-MS 锆石 U-Pb	[17]
	安徽祁门	变凝灰岩	830±5	LA-ICP-MS 锆石 U-Pb	[17]
	江西婺源	细砂岩	≤842	SHRIMP 锆石 U-Pb	[21]
	江西修水	石英砂岩	≤849	LA-ICP-MS 锆石 U-Pb	[7]
溪口岩群	安徽休宁	牛屋组砂岩	≤827	LA-ICP-MS 锆石 U-Pb	[18]
	安徽祁门	木坑组砂岩	≤830	LA-ICP-MS 锆石 U-Pb	[18]
	安徽祁门	板桥组细砂岩	≤833	LA-ICP-MS 锆石 U-Pb	[18]
	江西婺源	佛子坑组砂岩	≤840	LA-ICP-MS 锆石 U-Pb	[19]
	安徽祁门	砂岩	≤839	SHRIMP 锆石 U-Pb	[21]
	安徽休宁	砂岩	≤837	SHRIMP 锆石 U-Pb	[21]
	安徽休宁	砂岩	≤842	SHRIMP 锆石 U-Pb	[21]
	安徽祁门	砂岩	≤835	SHRIMP 锆石 U-Pb	[76]
	安徽祁门	砂岩	≤838	SHRIMP 锆石 U-Pb	[76]
	安徽祁门	砂岩	≤842	SHRIMP 锆石 U-Pb	[76]
万年群	江西万年	云母片岩	≤826	SHRIMP 锆石 U-Pb	[64]
新元古代中期弧后盆地蛇绿岩					
皖南伏川蛇绿岩	安徽歙县	辉长岩	819±3	LA-ICP-MS 锆石 U-Pb	[70]
	安徽歙县	辉长岩	822±3	LA-ICP-MS 锆石 U-Pb	[70]
	安徽歙县	辉长岩	827±3	LA-ICP-MS 锆石 U-Pb	[70]
	安徽歙县	辉长岩	824±3	SHRIMP 锆石 U-Pb	[69]
	安徽歙县	橄榄岩	827±9	SHRIMP 锆石 U-Pb	[62]
新元古代中期同造山花岗岩					
九岭岩体	江西宜丰	二长花岗岩	823±2	LA-ICP-MS 锆石 U-Pb	[73]
	江西武宁	花岗闪长岩	819±9	锆石 U-Pb	[13]
	江西宜丰	花岗闪长岩	820±10	SHRIMP 锆石 U-Pb	[71]
	江西万载	花岗闪长岩	828±8	SHRIMP 锆石 U-Pb	[71]

续表1

岩石单元	地理位置	岩石定名	年龄/Ma	测试方法	数据来源
休宁岩体	安徽休宁	花岗闪长岩	824±7	LA-ICP-MS 锆石 U-Pb	[14]
	安徽休宁	花岗闪长岩	825±7	LA-ICP-MS 锆石 U-Pb	[14]
	安徽休宁	花岗闪长岩	826±6	LA-ICP-MS 锆石 U-Pb	[72]
许村岩体	安徽歙县	花岗闪长岩	823±8	锆石 U-Pb	[13]
	安徽歙县	花岗闪长岩	823±7	LA-ICP-MS 锆石 U-Pb	[14]
	安徽歙县	花岗闪长岩	827±7	LA-ICP-MS 锆石 U-Pb	[14]
歙县岩体	安徽歙县	花岗闪长岩	823±9	LA-ICP-MS 锆石 U-Pb	[14]
	安徽歙县	花岗闪长岩	824±6	LA-ICP-MS 锆石 U-Pb	[14]
新元古代中期同造山变形变质					
东乡-歙县断裂带	安徽歙县	花岗质糜棱岩	768±30	白云母 $^{40}Ar/^{39}Ar$	[83]
	江西德兴	糜棱岩化闪长岩	793±1	角闪石 $^{40}Ar/^{39}Ar$	[35]
	江西德兴	糜棱岩化花岗岩	799±9	青铝闪石 $^{40}Ar/^{39}Ar$	[83]
新元古代中期后造山-裂谷型火山-沉积岩					
河上镇群	安徽休宁	上墅组英安岩	773±7	LA-ICP-MS 锆石 U-Pb	[26]
	浙江开化	上墅组凝灰岩	779±7	LA-ICP-MS 锆石 U-Pb	[26]
	浙江富阳	上墅组流纹岩	792±5	SHRIMP 锆石 U-Pb	[24]
	安徽休宁	上墅组流纹斑岩	794±7	LA-ICP-MS 锆石 U-Pb	[25]
	安徽休宁	上墅组流纹岩	797±6	LA-ICP-MS 锆石 U-Pb	[25]
	浙赣交界	上墅组流纹岩	797±5	LA-ICP-MS 锆石 U-Pb	[25]
	江西德兴	上墅组玄武岩	802±8	LA-ICP-MS 锆石 U-Pb	[25]
	浙江富阳	虹赤村组火山岩	797±11	SHRIMP 锆石 U-Pb	[77]
	安徽休宁	砂岩	≤810	LA-ICP-MS 锆石 U-Pb	[19]
	浙江富阳	杂砂岩	≤860	LA-ICP-MS 锆石 U-Pb	[112]
	浙江富阳	骆家门组砾岩	≤863	LA-ICP-MS 锆石 U-Pb	[94]
桃源组	江西广丰	桃源组流纹岩	803±9	SHRIMP 锆石 U-Pb	[78]
铺岭组	安徽祁门	铺岭组凝灰岩	751±8	LA-ICP-MS 锆石 U-Pb	[25]
	安徽祁门	铺岭组凝灰岩	763±12	LA-ICP-MS 锆石 U-Pb	[25]
	安徽祁门	铺岭组流纹岩	765±7	LA-ICP-MS 锆石 U-Pb	[25]
休宁组	安徽祁门	休宁组砾岩	≤763	LA-ICP-MS 锆石 U-Pb	[94]
	安徽祁门	休宁组砂岩	≤751	LA-ICP-MS 锆石 U-Pb	[18]
硐门组	江西修水	硐门组砂岩	≤753	LA-ICP-MS 锆石 U-Pb	[18]
马涧桥组	江西都昌	马涧桥组碎屑岩	≤769	SHRIMP 锆石 U-Pb	[16]
新元古代中期后造山-裂谷型花岗岩					
石耳山杂岩	浙江开化	齐溪田岩体	775±5	LA-ICP-MS 锆石 U-Pb	[26]
	江西婺源	莲花山岩体	771±17	SHRIMP 锆石 U-Pb	[26]
	江西婺源	莲花山岩体	777±7	LA-ICP-MS 锆石 U-Pb	[26]
	江西婺源	莲花山岩体	795±9	LA-ICP-MS 锆石 U-Pb	❶
	江西婺源	莲花山岩体	793±12	LA-ICP-MS 锆石 U-Pb	❶
	江西婺源	灵山岩体	779±10	LA-ICP-MS 锆石 U-Pb	❶
	江西婺源	栗木坑岩体	789±11	LA-ICP-MS 锆石 U-Pb	❶
道林山杂岩	浙江富阳	花岗岩	775±13	SHRIMP 锆石 U-Pb	[79]
	浙江富阳	花岗岩	780±6	LA-ICP-MS 锆石 U-Pb	[79]

❶徐先兵,陈能松,章泽军,等. 江西省1:5万清华、江湾幅区域地质调查报告[R]. 武汉:中国地质大学(武汉)地质调查研究院,2014.

续表1

岩石单元	地理位置	岩石定名	年龄/Ma	测试方法	数据来源
道林山杂岩	浙江富阳	花岗岩	794±9	SHRIMP 锆石 U-Pb	[24]
新元古代中期后造山-裂谷型中-基性脉岩					
	江西婺源	闪长岩	788±7	LA-ICP-MS 锆石 U-Pb	[76]
	江西德兴	闪长岩	784±27	锆石 U-Pb	[74]
	江西安义	辉绿岩	796±1	锆石 U-Pb	[75]
	江西浮梁	辉长岩	801±4	LA-ICP-MS 锆石 U-Pb	[25]
	安徽歙县	复合岩墙	804±7	LA-ICP-MS 锆石 U-Pb	[25]
	安徽歙县	复合岩墙	805±4	LA-ICP-MS 锆石 U-Pb	[25]
早古生代变形变质					
	安徽休宁	糜棱岩	429±3	白云母 $^{40}Ar/^{39}Ar$	[87]
	安徽婺源	糜棱岩/走滑	449±4	白云母 $^{40}Ar/^{39}Ar$	[32]
NNE 向	江西弋阳	变玄武岩	413±8	全岩 $^{40}Ar/^{39}Ar$	[86]
东乡—歙县	江西弋阳	变玄武岩	435±9	斜长石 $^{40}Ar/^{39}Ar$	[86]
断裂带	江西弋阳	变玄武岩	413±8	全岩 $^{40}Ar/^{39}Ar$	[86]
	江西弋阳	变玄武岩	459±9	斜长石 $^{40}Ar/^{39}Ar$	[86]
近东西向剪切带	安徽婺源	糜棱岩/走滑	429±3	白云母 $^{40}Ar/^{39}Ar$	[32]
	江西弋阳	云母片岩/逆冲	421±8	白云母 $^{40}Ar/^{39}Ar$	[84]
E-W-NEE 向	江西弋阳	黑云母片岩/逆冲	428±2	黑云母 $^{40}Ar/^{39}Ar$	[84]
江山—绍兴	浙江诸暨	变辉长岩	426±2	角闪石 $^{40}Ar/^{39}Ar$	[64]
断裂带	浙江诸暨	变质泥岩	425±7	黑云母 $^{40}Ar/^{39}Ar$	[64]
	浙江诸暨	混合岩	433±3	SHRIMP 锆石 U-Pb	[64]
	江西万年	云母片岩	438±3	白云母 $^{40}Ar/^{39}Ar$	[64]
近 E-W 向	江西万年	云母片岩	420±3	白云母 $^{40}Ar/^{39}Ar$	[64]
万年韧性剪切带	江西万年	云母片岩/逆冲	429±1	白云母 $^{40}Ar/^{39}Ar$	[35]
	江西万年	云母片岩/逆冲	428±1	白云母 $^{40}Ar/^{39}Ar$	[35]
	江西宜丰	糜棱状花岗岩/逆冲	468±12	白云母 $^{40}Ar/^{39}Ar$	[39]
近 E-W 向	江西万载	糜棱状花岗岩/走滑	386±6	黑云母 $^{40}Ar/^{39}Ar$	[39]
南昌—万载剪切带	江西万载	糜棱状花岗岩/走滑	382±2	黑云母 $^{40}Ar/^{39}Ar$	[39]
	江西宜丰	糜棱状花岗岩/走滑	379±4	白云母 $^{40}Ar/^{39}Ar$	[39]
早中生代变形变质					
	安徽歙县	糜棱岩	231±2	白云母 $^{40}Ar/^{39}Ar$	[87]
NNE 向	江西婺源	糜棱岩	257±2	白云母 $^{40}Ar/^{39}Ar$	[87]
东乡—歙县	江西德兴	变辉长岩	233±5	斜长石 $^{40}Ar/^{39}Ar$	[86]
断裂带	江西德兴	淡色花岗岩	229±13	SHRIMP 锆石 U-Pb	[23]
	江西弋阳	变辉长岩	266±5	斜长石 $^{40}Ar/^{39}Ar$	[86]
早中生代岩浆					
	江西上高	蒙山花岗岩	236±3	LA-ICP-MS 锆石 U-Pb	[81]
蒙山岩体	江西上高	蒙山花岗岩	220±3	LA-ICP-MS 锆石 U-Pb	[81]
	江西上高	蒙山花岗岩	217±1	LA-ICP-MS 锆石 U-Pb	[81]
	江西上高	蒙山花岗岩	218±2	SIMS 锆石 U-Pb	[39]

造变形以中浅层次变形为主,表现为北北东褶皱逆冲构造[89−91]。韧性变形主要发育在赣东北断裂带中,其形成峰期时代为230 Ma左右[23,59,86,88]。

5 构造演化

江南造山带东段及其邻区出露的最古老的地层为其东南缘的中元古代晚期(1172~1015 Ma)变沉积岩和变火山岩,地球化学指示沉积环境为被动大陆边缘[5,92−94]。新元古代早期(1000~890 Ma)弋阳—德兴蛇绿岩带、双溪坞群岛弧型火山岩以及钙碱性花岗岩的发育指示扬子东南缘由被动大陆边缘转化为活动大陆边缘[6,57−60,95−97]。随着俯冲作用的进行,双溪坞岛弧与扬子陆块沿弋阳—德兴断裂带发生弧—陆碰撞,形成新元古代早期(880~860 Ma)淡色花岗岩、高压蓝片岩、NNE向褶皱−逆冲推覆构造以及弧后前陆盆地等[1,3,23,29,30]。

新元古代中期(约850 Ma),扬子陆块北缘开始大洋俯冲[7],导致江南造山带东段的北缘庐山地区发育岛弧岩浆活动[43,44]。强烈的弧后伸展作用导致扬子板块大规模的中基性岩浆活动和弧后盆地的形成[19,21,24,61−66]。随着弧后盆地的扩张,皖南伏川新元古代中期(827~819 Ma)蛇绿岩开始发育[69,70],且弧后盆地接受巨厚的泥砂质复理石沉积。其后,持续的俯冲作用导致弧后盆地发生关闭、扬子和华夏陆块的陆−陆碰撞作用以及江南造山带的形成[19]。强烈的碰撞作用形成过铝质花岗岩[13,14]、近E−W向褶皱和逆冲推覆构造[27,30−32]以及NNE向左旋走滑剪切变形[29]。

南华纪初期,江南造山带开始发生后造山伸展垮塌和裂谷作用[19,22,25,26]。伸展作用开始于约810 Ma[19],以发育南华纪早期(805~750 Ma)双峰式火山岩、后造山花岗岩以及基性岩浆活动为特征,并接受巨厚的碎屑岩沉积[18,98]。其后,江南造山带因全球新元古代"雪球事件"广泛发育冰川并接受冰碛物和滨浅海相沉积[51,52,99]。

江南造山带东段核部未见上下古生界之间的直接接触关系,其北缘上下古生界之间表现为平行不整合接触。在江南造山带东段东南缘的早古生代浙西北前陆盆地中[100,101],上下古生界的接触关系由南至北分别表现为高角度不整合、低角度不整合以及平行不整合[90,91,102],指示广西期造山作用由南向北减弱。江南造山带东段九岭南缘与障公山南缘均发育广西期同造山期由南向北的逆冲作用与后造山期近东西向右旋韧性剪切变形[32,39]。在江山—绍兴断裂带以北江南造山带及其邻区,广西期岩浆活动的信息仅保存于白垩纪花岗岩之中[103]。而在江山—绍兴断裂带以南,广西期造山作用却表现为面状分布的强烈褶皱和韧性变形、S型花岗岩侵位、麻粒岩相−角闪岩相变质作用以及深熔作用[64,84,104−109]。相较而言,江南造山带东段广西期岩浆活动和变质较弱,但变形程度基本相当。以上证据表明,江南造山带东段万载—南昌—景德镇—歙县断裂带以南地区卷入了华南早古生代造山作用。

江南造山带晚古生代深海相沉积被上三叠统—中侏罗统陆相沉积角度不整合覆盖[110],指示江南造山带东段在早中三叠世发育印支期造山作用。构造变形主要表现为NNE向褶皱—逆冲构造,且发育约230 Ma韧性变形和高级变质作用[23,59,88]。另外,江南造山带东段还零星可见三叠纪花岗岩活动[39,71]。以上地质特征与华南印支期造山作用所产生的地质效应基本一致[110−114],指示江南造山带卷入了华南印支期造山运动。江南造山带NNE向褶皱—逆冲构造可能是华南板块在北部华北板块、南部印支板块以及东北古太平洋板块联合作用的结果[89,110]。印支期造山作用基本奠定了江南造山带东段的构造变形特征[8]。

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