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华南新元古代多地体汇聚—拼贴与资源效应

李军勇[1]，王孝磊[1]，谷志东[2]，黄煜[1]，王国光[1]

1.南京大学地球科学与工程学院，南京 210023

2.中国石油勘探开发研究院，北京 100083

摘 要 【目的】新元古代是华南板块演化过程中的重要阶段，该时期的岩石记录了丰富的地壳增生、再造和重塑信息，并奠定了华南板块的物质基础。深入研究华南板块新元古代的地壳演化历史对理解华南板块的资源环境效应、全球新元古代超大陆聚合和离散以及后续的生命大爆发等重大事件具有重要的意义。【方法】通过梳理华南板块新元古代早—中期的重要地质记录，指出华南板块及其周边地区在新元古代可能长期存在海陆格局和多个地体（或微陆块），而地体边界可由一系列的主动和被动大陆边缘岩石单元约束。【结果与结论】华南板块在新元古代时期表现出来的与汇聚造山有关的俯冲带物质循环、岩浆和变质记录、增生杂岩、构造变形等关键证据共同表明，华南板块在新元古代早—中期可能存在长期的增生型造山作用和与之相关的多地体向扬子陆块的汇聚—拼贴过程。该增生造山和多地体汇聚过程较早以扬子北部为汇聚核心，随后由于地体拼贴主动大陆边缘逐步向外迁移而扩张，大陆不断增生，最终造就了现今华南板块的大体格局。同时，地体汇聚边界成为显生宙壳幔相互作用和地壳再造和分异的重要地区，很可能在显生宙的成矿过程中发挥了重要作用，这为研究基底组成特征与显生宙成矿作用之间的联系提供了一个新思路。

关键词 华南板块；新元古代；俯冲增生；多地体汇聚；资源效应

第一作者简介 李军勇，男，1993 年出生，博士后，岩石学，E-mail: ljy@nju.edu.cn

通信作者 王孝磊，男，博士，教授，E-mail: wxl@nju.edu.cn

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0 引言

华南板块东邻太平洋板块、北以秦岭—大别—苏鲁造山带与华北板块相连、南以哀牢山—松马缝合带与印支板块相邻、西以龙门山推覆带与松潘—甘孜地体相接，主要由扬子和华夏两个陆块组成，是东亚重要的古老板块之一[1]。它经历了自太古宙以来多阶段的块体增生、再造和不同性质与规模的构造和岩浆运动的复合、叠加与改造[2-4]，被卷入了地球历史上几个主要的超大陆和巨大陆的聚合和离散过程中。尽管目前对于华夏地块东部的构造属性存在一些争议[5-7]，华南板块的主体构造格架总体上被认为在新元古代时期形成，并伴随着西北侧的扬子陆块和东南侧的华夏陆块沿江南造山带拼接[8-14]。分布于扬子和华夏陆块的前寒武纪岩石共同记录了从太古宙陆核形成、古元古代碰撞造山、中元古代大陆裂

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解，到新元古代增生造山和裂解等一系列构造演化信息[14-20]。这些前寒武纪基底岩石单元和构造框架奠定了华南的地壳物质基础，且作为显生宙成岩成矿的物质和构造基础，具有重要的研究价值[2,4,21]。尤其是，近年来前寒武纪岩石学、地球化学、地质年代学和地球物理的研究一致表明，扬子和华夏陆块本身在地壳物质组成上均非“铁板一块”，可能存在多个不同基底配置的地体（或微陆块）的拼合[3,20,22-26]，而新元古代（主要在ca.1.0~0.6 Ga）作为华南被卷入全球构造运动较显著的时期，很可能是地体（或微陆块）相互汇聚的重要时期，值得深入研究。

在全球碎屑锆石和岩浆锆石的年龄频率分布图中，新元古代早—中期并没有呈现出明显的峰[27]，但该期岩石却在华南板块出露良好且分布广泛（图1）。其中，岩浆岩的时代断续分布在1 000~620 Ma，并伴有860~542 Ma连续的沉积岩记录，以及一些新元古代早—中期（880~750 Ma）的中—高级变质岩记录。这些岩石主要分布在板块边界，总体上表现为两类出露形式：（1）中—上地壳尺度的杂岩体，主要分布在现在的攀西—汉南带、秦岭—大别—苏鲁造山带中[28-33]；（2）上地壳尺度的火山—沉积岩和花岗岩体，主要分布在江南造山带和华夏陆块中[4,10,13-14]。此外，扬子陆块的陆核地区（崆岭地区）和四川盆地内部超深钻孔岩心也记录了这个时期的岩浆和沉积过程[34-37]。由于该阶段岩浆岩的地球化学特征多样、年龄跨度大，且沉积岩的组成特征、物源和沉积背景也不尽相同，关于它们的成因解释、构造背景及其对应的地壳演化过程长期以来存在争议。近年来，笔者和一些学者提出，这些岩石的形成可能主要与新元古代的增生型造山作用有关，反映了长时间尺度的大洋岩石圈俯冲（和/或回卷）作用引发的地壳增生、再造和重塑过程[13,38-40]。本文在梳理华南新元古代增生型造山作用关键证据的基础上，聚焦华南新元古代时期的多地体汇聚—拼贴过程，并探讨该过程如何影响显生宙资源的形成和分布。

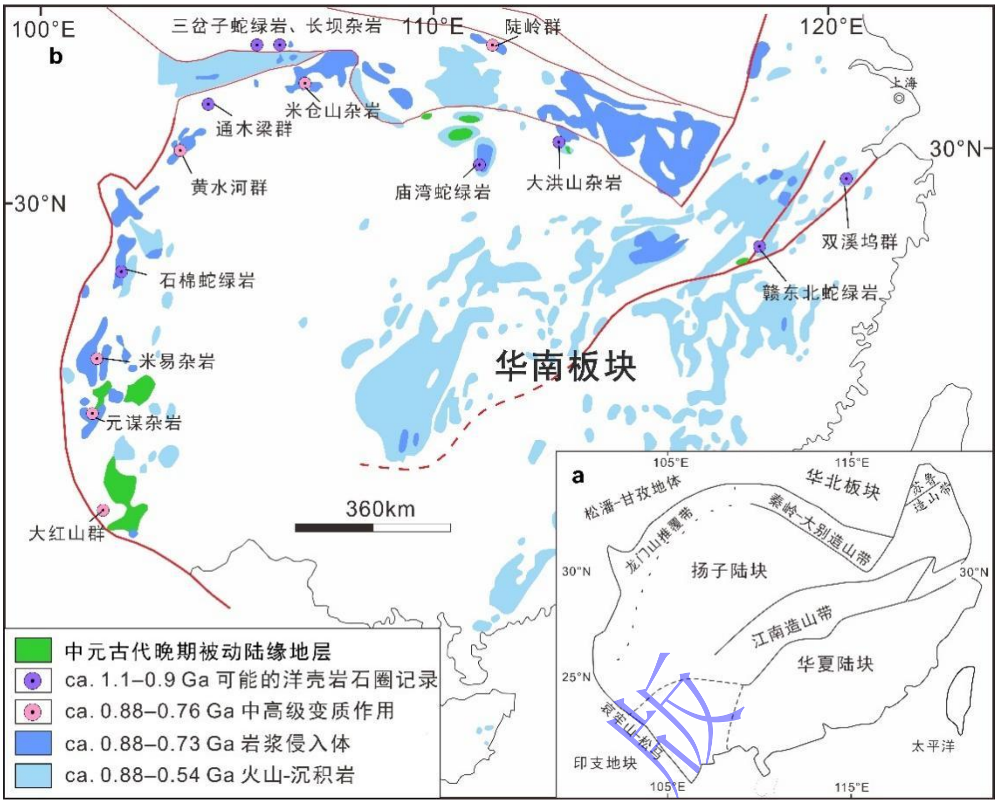

图1 华南板块主要构造岩石单元和新元古代岩石分布简图

（a）华南板块的组成单元及邻区板块（或地体）的构造关系图；（b）华南板块中元古代晚期—新元古代岩石的分布图（据文献[1]修改）

Fig.1 Simplified geological maps showing the widespread distribution of the Neoproterozoic rocks within the South China Block

(a) tectonic map showing the division of the South China Block and its tectonic relationships with other continents or terranes; (b) Late Mesoproterozoic to Neoproterozoic rock distribution within the South China Block (modified from reference [1])

1 新元古代全球构造演化和华南的响应

新元古代是地球历史上一个重要的过渡阶段——由中元古代的“造山减弱”[41]、“造山沉寂”[42]或广泛的“热造山作用”[43]转变为显生宙全球范围活跃的现代板块构造体制[44-46]。该时期广泛出现了深俯冲相关的岩石和构造单元，例如线性分布的陆缘弧和弧后盆地、蛇绿岩、蓝片岩和冷的榴辉岩等[45,47-48]，暗示了活跃的汇聚造山作用。该时期也是全球超大陆和巨大陆演化的重要阶段，包括了罗迪尼亚超大陆的最终形成、完全裂解以及随后的冈瓦纳巨大陆聚合过程[49-51]。

罗迪尼亚超大陆主体的聚合发生在 ca. 1 100~900 Ma，伴随有早期阶段的内部大陆的碰撞造山和晚阶段外围陆块的逐步汇聚作用。到了新元古代中期，全球进入了长时期以裂解为主导的构造过程。近年来，研究者发现从罗迪尼亚超大陆裂解到冈瓦纳巨大陆聚合期间，

地球具有地幔二阶结构（Degree-2），包括两个赤道附近的上升流和沿着经线分布的环超大陆俯冲带（图2）[52-53]。伴随着超大陆裂解，其外围的陆块相继向外迁移，同时被卷入长期的增生型造山作用，例如印度西北部（至少ca. 1 000~820 Ma）[54]、塔里木（ca. 950~600 Ma）[55]、西非（ca. 880~680 Ma）[56]等。直到新元古代末期，地球又进入到新一轮巨大陆的聚合阶段。华南的扬子和华夏陆块通常被认为处于罗迪尼亚超大陆的边缘地区。其中，扬子陆块西缘和西北缘被认为与印度西北缘、马达加斯加和塞舌尔地区类似，长期处于主动大陆边缘的环境，并与环绕罗迪尼亚超大陆的开阔大洋岩石圈发生相互作用[57]。地幔二阶结构模型能够较好地解释新元古代早—中期全球大陆碰撞记录（如超高压变质岩等）的相对缺乏[47]，也反映了从罗迪尼亚超大陆裂解出去的板块（或微陆块）与大洋板块长时间尺度的相互作用过程。同时，在该模型的背景下，由于大洋和大陆板片的迁移速度不同以及俯冲大洋板片回卷（或断离）等因素，主动大陆边缘常常会伴随着周期性的前进型和后撤增生型造山作用。

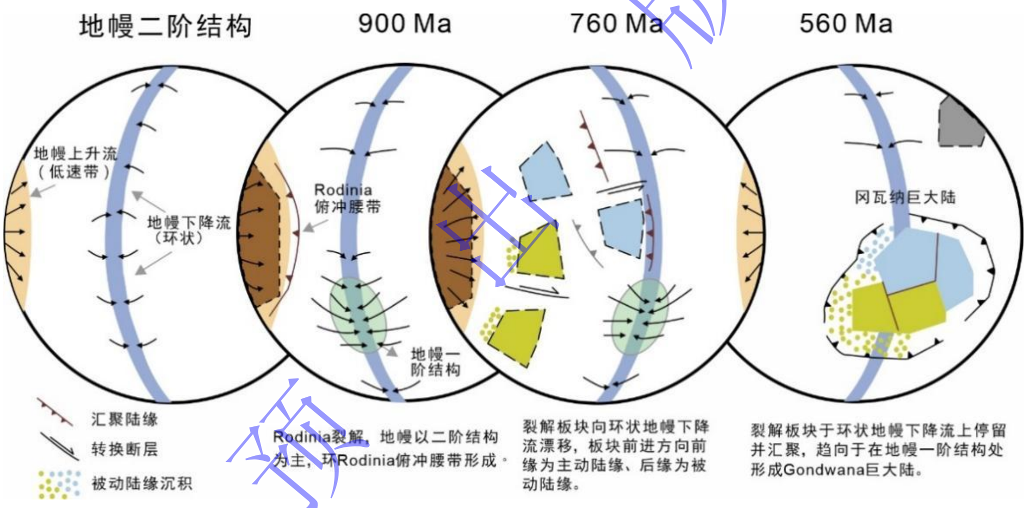

图2 新元古代时期地幔二阶段模式简图

该模式展示了罗迪尼亚超大陆裂解过程中，板块从地幔上升域向环状地幔下降流方向运移，随后在地幔下降流的轨道上汇聚形成冈瓦纳巨大陆的过程（据文献[52-53]修改）

Fig.2 Schematic of the degree-2 mantle convection during the Neoproterozoic

The model demonstrates that the continental blocks migrated from mantle upwelling zone towards the great cycle of mantle downwelling during the Rodinia breakup, and then converged to form Gondwana over the locus of downwelling (modified from references [52-53])

2 华南新元古代的多地体格局

华南的多地体格局可能在中元古代晚期已初步塑造。随着全球哥伦比亚超大陆的裂解，华南陆块在古元古代晚期—中元古代以伸展—裂谷型构造为主，且该过程主要表现在扬子陆块的南部：经历了至少三期（~1.7 Ga，~1.5 Ga和~1.05 Ga）短暂的裂谷岩浆作用，伴随有巨厚的盆地沉积[20]。与之不同的是，扬子陆块北部地区在古元古代（ca.1.85 Ga之前）完

成克拉通化后[58]，较少地被卷入哥伦比亚超大陆裂解的构造和岩浆活动；其具有厚的岩石圈根（>160 km）[59-60]，缺失了古元古代—新元古代早期大套的沉积记录，暗示了这个阶段长期以稳定大陆岩石圈存在的背景。

中元古代晚期的裂解事件可能成功促使了板块裂解，导致扬子陆块内部及边缘出现一系列蛇绿岩套（如：石棉、庙湾和赣东北蛇绿岩）（其构造就位时间要晚于蛇绿岩套岩石的结晶时间）[61-64]和不同地区分布的被动大陆边缘火山—沉积记录（如：扬子陆块西南缘的昆阳群和会理群，扬子陆块北缘的马槽园群、神农架群和打鼓石群，扬子陆块东南缘的田里岩群和铁砂街群等）[19,65-67]，表明当时可能已经广泛出现海陆格局和潜在的多个地体（图3）。到了新元古代，被动陆缘向主动陆缘转换，华南陆块出现了更多主动大陆边缘的岩石构造单元，包括：（1）蛇绿岩套，如前人报道的三岔子蛇绿岩、花山蛇绿岩[68-69]；（2）洋内弧岩浆岩，如通木梁火山岩、双溪坞火山岩、长坝火山岩、大洪山火山岩等[70-73]；（3）大陆弧及相关弧后沉积盆地，如“攀西—汉南”钙碱性岩浆岩带、江南造山带褶皱地层等[10-11]；（4）增生杂岩记录，如大洪山增生杂岩、长坝增生杂岩、黄水河增生杂岩等[40,73-75]。

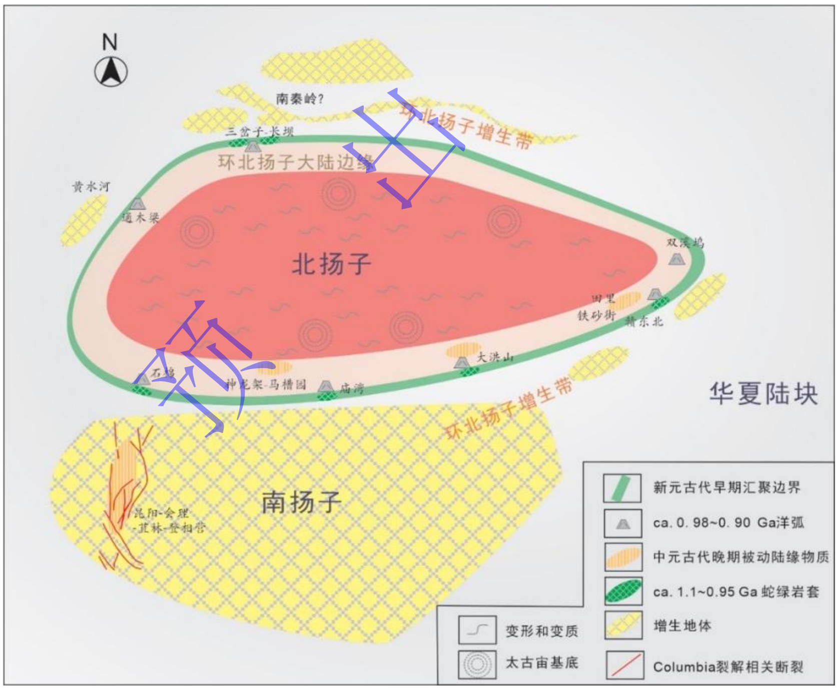

图3 扬子陆块新元古代早期的环状基底结构模型和多地体格局示意图（据文献[20]修改）

太古宙基底主导的北扬子与古元古代—中元古代基底主导的地体通过新元古代的造山带相连。扬子陆块在新元古代早期可划分为南北两个部分，围绕着北扬子有一系列的大洋板片俯冲和相关的汇聚边界发育

Fig.3 Cartoon illustrating zoned basement structure and multi-terrane pattern of the Yangtze Block (modified from reference [20])

The Archean-affinity core was bounded with Paleoproterozoic-Neoproterozoic terranes by Neoproterozoic orogens. The Yangtze Block could be divided into north and south during the Early Neoproterozoic, while the north Yangtze was surrounded by a series of oceanic subduction and associated convergent boundaries

综合中元古代晚期到新元古代早—中期的地质记录，笔者认为，华南在新元古代存在多个地体（或微陆块）长期增生的海陆格局，而地体边界可由上述主动和被动大陆边缘岩石单元大致约束。扬子陆块北部（或北扬子）可能代表了新元古代早期汇聚作用的中心（汇聚时间跨度大，ca. 1 000~730 Ma），其周围的地体（包括哥伦比亚超大陆裂解相关的地体、洋岛弧、洋壳残片等）相继增生到北扬子，伴随着主动大陆边缘的向外迁移而扩张，大陆不断增生，最终造就了现今华南板块的大体格局（图3）。

3 新元古代汇聚作用的关键证据

华南陆块在新元古代早期（ca. 1 000~900 Ma）的构造背景以汇聚为主，不同的构造模式在此认识上并无太大的争议。该时期的岩石记录相对较少，主要以岛弧岩浆岩和蛇绿岩残片的形式零星分布在扬子陆块的西、中、北、东部地区。到了新元古代早—中期（880~720 Ma），扬子陆块的构造、岩浆和沉积活动非常活跃，开始出现大规模的岩浆岩和沉积序列：其西缘和西北缘以攀西—汉南岩浆岩杂岩带（单个杂岩体上分布有不同时代不同类型的岩浆岩，伴有较少的变质岩）为主，而东南缘记录了扬子和华夏陆块之间的聚合和裂解过程相关的岩浆—沉积序列（江南造山带）。关于它们的成因解释、构造背景及其对应的地壳演化过程存在争议。这些争论主要围绕两种不同的构造和岩浆演化模型展开：（超级）地幔柱驱动的伸展型构造和岩浆过程和造山作用驱动的汇聚型构造和岩浆过程，两种模型在构造体制影响的时间上也有不同的解释。

笔者结合最近几年自身和其他学者的研究，认为华南新元古代早—中期可能分为两个阶段，至少在早阶段（ca. 880~810 Ma）活跃的构造、岩浆和沉积活动与多地体汇聚—拼贴及其相关的增生型造山作用有关。下面列举几个关键的证据。

3.1 弧前沉积物的弧内快速循环

汇聚型大陆边缘的构造演化常伴随着显著的地壳物质再循环。传统上，地壳物质循环被认为主要通过俯冲的大洋板片进行。在这个过程中，大洋板片可以携带洋壳沉积物和从陆壳底部剥蚀下来的物质进入地幔深度，在深部发生部分熔融，产生的熔体底辟上升加入上部板块的底部[76-77]。近年来，许多学者发现地壳物质再循环也可以在弧陆壳内部进行，该过程则通常是通过弧前或弧后的大规模挤压型断层，将浅部地壳的物质运移并底垫到更深部的地壳中[78-79]。该过程可以把地表沉积物埋深至超过30 km的深度，并伴随着沉积物的变质或者部分熔融[79]。以上壳外和壳内两种地壳循环机制在世界上主要的大陆弧均有报道，包括澳洲拉克兰造山带、日本岛弧以及科迪勒拉陆弧系统[80-82]。

近期，笔者对华南陆块西缘黄水河群中出露的条带状混合岩开展了年代学和岩石成因学分析，发现该混合岩原岩为一套新元古代的弧前沉积岩，其中的碎屑锆石年龄集中在 ca. 830~870 Ma，深熔年龄为 829±23~814±14 Ma（图 4）[29]。其中的锆石普遍有核边结构，边部锆石的δ^{18}O 值（9.3‰~13.4‰）显著高于锆石核部（图 4），这表明样品可能经历过地表的低温水—岩交换反应。相平衡模拟显示其深熔温度和压力分别为~670 ℃和 5.9~8.1 kbar，对应的地温梯度（83~114 ℃/kbar 或者 25~34 ℃/km）与有持续岩浆供给的大弧地壳的地温梯度相吻合。以上结果表明，在华南板块西缘记录了如下的汇聚型物质循环过程：弧前沉积物在地表完成沉积后，在很短的时间尺度内（<10 Myr）被运移至地壳深部的弧前地区并发生深熔作用，而运移通道很可能是陆内的推覆断层系统而不是俯冲板片上方“隧道”。这样的弧内推覆相关的变质深熔过程在世界上许多典型的陆弧系统中可以见到[78-79]。

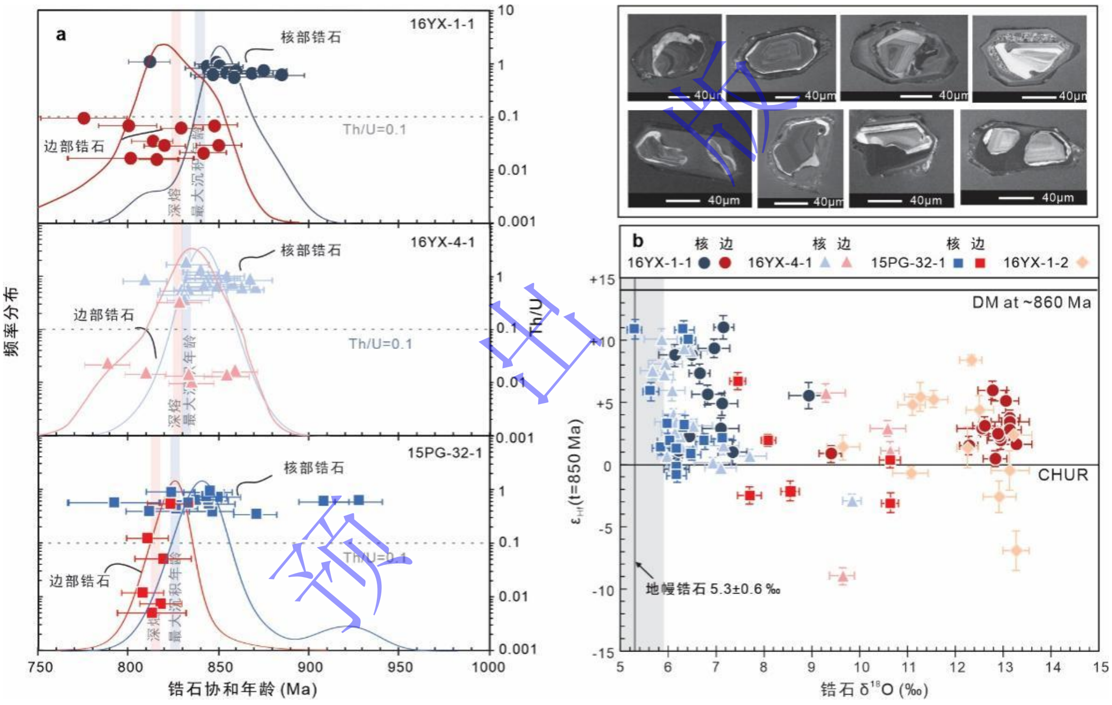

图4 黄水河群混合岩中锆石年龄-Hf-O同位素分布图（据文献[29]修改）

黄水河群混合岩中锆石核部和边部具有显著的年龄-Hf-O同位素差异，支持弧前沉积岩经历了快速的弧内循环过程

Fig.4 Zircon U-Pb-Hf-O isotopic distributions of the Huangshuihe migmatites (modified from reference [29])

The significant difference of ages and Hf-O isotopes between zircon core and rim domains of the migmatites in the Huangshuihe Group could be caused by rapid intra-arc recycling of fore-arc sediments

3.2 俯冲带变质作用

俯冲带变质作用可以根据发生的位置划分为俯冲板块型和上覆板块型。前者发生在俯冲带下盘的洋壳，由于俯冲洋壳通常具有较低的地温梯度（5~15 ℃/km），因而变质作用的温压比（*T*/*P*）也很低；后者发生在俯冲带上盘，受控于俯冲板片角度、俯冲速率等因素，上盘不同区域位置可能对应不同的地温梯度，因而变质温压比可能具有较大的范围

（15~50 ℃/km）[83]。较早在江南造山带德兴—西湾一带发现的蓝闪石片岩和硬玉石英片岩，其矿物对温压计算显示其属于高压低温变质作用的产物，蓝闪石K-Ar定年结果为866±14 Ma，可能反映了新元古代的俯冲板块型变质作用[84]。近年来，在攀西—汉南杂岩带和南秦岭北部地区，已陆续报道了与新元古代汇聚造山作用有关的中、高级变质作用。它们的变质时代介于880~760 Ma，包括在彭灌杂岩中报道的860~810 Ma的角闪岩相变质作用[29]，米仓山杂岩中报道的ca. 800 Ma的角闪岩相—麻粒岩相变质作用[28]，元谋—米易杂岩中报道的880~760 Ma的绿帘角闪岩相—角闪岩相变质作用[30-31]，大红山群中报道的ca. 845 Ma的角闪岩相变质作用[85]，和南秦岭的陡岭地体中报道的ca. 817 Ma的角闪岩相变质作用[33]等。这些变质作用具有相对低温、中—高压的特点，与大陆弧的地温梯度或者热俯冲地温梯度一致（图5a），很可能指示了新元古代大洋岩石圈的俯冲效应。

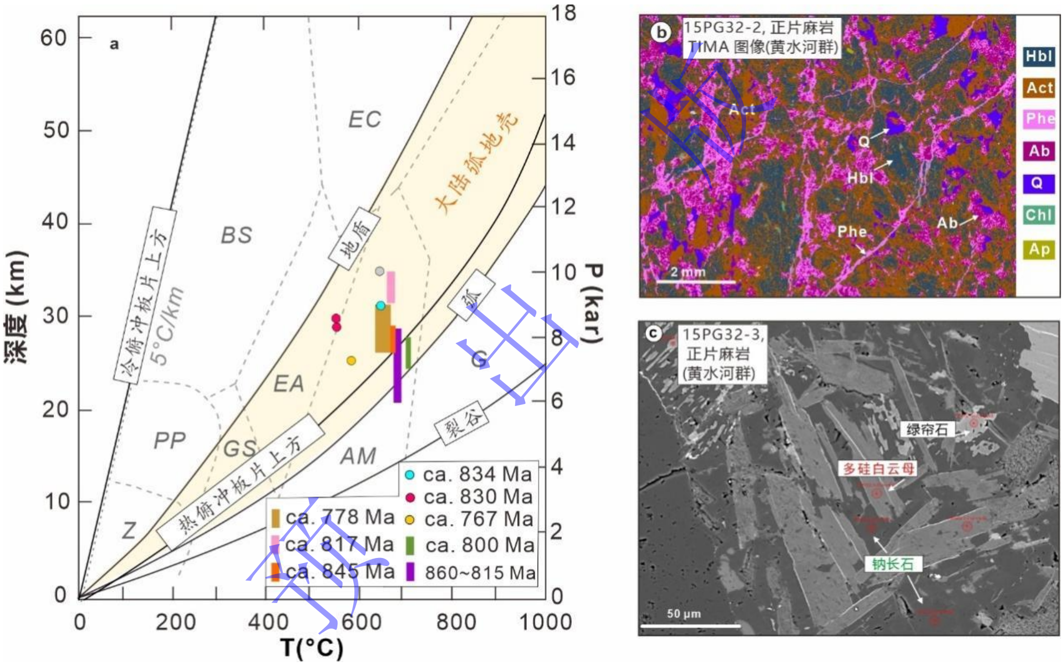

图5 扬子陆块新元古代早中期的俯冲带变质记录

（a）扬子陆块攀西—汉南带和南秦岭中已报道的新元古代峰期变质记录，数据来源于文献[28-31,33,40,85]；Z.沸石相；PP.葡萄石—绿纤石相；GS.绿片岩相；BS.蓝片岩相；EA.绿帘角闪岩相；AM.角闪岩相；EC.榴辉岩相；G.麻粒岩相；（b，c）扬子陆块西北缘黄水河群中保存的含多硅白云母的新元古代正片麻岩的岩相学特征[40]；TIMA.Tescan矿物综合面扫图；Act.阳起石；Hbl.角闪石；Q.石英；Ab.钠长石；Phe.多硅白云母；Chl.绿泥石；Ap.磷灰石

Fig.5 Subduction-zone metamorphic records of the Yangtze Block

(a) The Neoproterozoic peak metamorphic conditions reported in the Panxi-Hannan Belt and South Qinling (data from references [28-31,33,40,85]); Z. zeolite; PP. prehnite-pumpellyite; GS. greenschist; BS. blueschist; EA. epidote-amphibolite; AM. amphibolite; EC. eclogite; G. granulite; (b.c) Petrographic features of the phengite-bearing orthogneiss, which is found in the Huangshuihe Group, NW Yangtze[40]; TIMA. Tescan Integrated Mineral Analyzer; Act. actinolite; Hbl. hornblende; Q. quartz; Ab. albite; Phe. phengite; Chl. Chlorite; Ap. apatite

近期，笔者在华南陆块西缘黄水河群中同样发现了一套新元古代正片麻岩，其展现出一致的新元古代变质年龄（ca. 830 Ma）[40]。变质岩中发育一套特征的低温、高压、富水变

质矿物组合（包括多硅白云母、阳起石、镁质角闪石、绿帘石、绿泥石等）（图5b，c）。其中多硅白云母是典型的俯冲带变质矿物之一。对其矿物相平衡模拟显示其经历了中压、低温的峰期变质作用（温度约为550 ℃；压力8~9 kbar），可能对应了上覆板块型俯冲变质作用[85]。

3.3 新元古代增生杂岩

增生杂岩形成于大洋岩石圈的俯冲地带，其岩石组合通常较复杂，可包含俯冲板片和俯冲上盘剥蚀下来的物质、洋弧、蛇绿岩残片、洋底高原、古老大陆板块、增生后花岗岩、高级变质岩（达到麻粒岩相）、高压—超高压变质岩和碎屑沉积盆地等[86]。华南典型的新元古代增生杂岩记录可能保存在江南造山带、扬子北缘以及攀西—汉南带和南秦岭的部分区域中。下面选取代表性增生杂岩进行介绍。

（1）江南造山带是新元古代时期发生在扬子地块东南缘以岛弧地体拼接为主的增生型造山带（如：王孝磊等[87]）。江南造山带东段包含一系列新元古代早期（ca. 970~850 Ma）的新生洋弧（以双溪坞群为主，包括弧火山岩、闪长岩、花岗闪长岩、少量的镁铁质—超镁铁质岩套和深海燧石岩）[13]、新元古代早期的赣东北蛇绿岩套（ca. 1 000~970 Ma），它们可能代表了新元古代增生到扬子陆块东南缘的一套洋壳岩系[20,87]。

（2）扬子陆块北缘的大洪山地区也出露了一套新元古代的俯冲增生杂岩[74-75]，它们包括浊积岩、海山玄武岩、洋盆硅质岩和蛇绿岩等洋壳岩石单元，并与ca. 870~800 Ma岩浆岩密切伴生。这些岩石呈现出无根的构造混杂岩特点，遭受了强烈的构造变形，褶皱、逆冲断裂发育。Huang *et al.* [72]对其中的长英质火山岩的测年结果为 ca. 970 Ma，Shi *et al.* [69]对其中蛇绿岩套中的辉长岩定年结果为ca. 947 Ma，这些表明该洋壳岩石单元的时代很可能为新元古代早期。

（3）扬子陆块西北缘的勉略带中包含新元古代早期的三岔子蛇绿岩残片（ca. 950~930 Ma）[68]和长坝洋弧岩浆岩（ca. 985~950 Ma）[73]，代表了洋壳岩石圈的岩石组合。该带中发育的ca. 900 Ma的斜长花岗岩和其后的大陆弧岩浆记录，代表了该洋壳岩石圈在新元古代中期已增生到活动大陆边缘。

（4）笔者在扬子陆块西缘攀西—汉南杂岩带内的黄水河群中厘定了一套原岩为ca. 1 400 Ma的正片麻岩，变质年龄为ca. 830 Ma，变质峰期温压为 550 ℃、8~9 kbar[40]。该时代的岩浆和锆石记录在扬子陆块均比较少见，可能代表了一套外来的地壳物质增生到扬子陆块西缘，伴随着新元古代的挤压推覆至中地壳深度。

总体来看，华南新元古代增生杂岩以早期的洋壳和岛弧岩块为主，伴有少量的外来岩

石单元。较老的增生杂岩（ca. 1 000~900 Ma）普遍与较年轻的（ca. 880~810 Ma）岩浆岩和变质岩在空间上密切伴生，一方面反映了活动大陆边缘长期的构造、增生和岩浆过程，另外一方面也暗示着增生杂岩在新元古代早中期已经就位到大陆边缘并参与了随后的构造过程。这些增生地体大都具有亏损的放射性同位素特征，被认为是扬子陆块周缘广泛出露的具有“新生”同位素特征的花岗岩的潜在源区[88-89]。

3.4 新元古代挤压变形事件

华南陆块与新元古代挤压变形记录以区域不整合面的形式显著表现在江南造山带和大洪山地区的地层中[2,9,87,90]。江南造山带内分布的新元古代地层大体可以将此区域不整合面分为上下两部分：下部地层以冷家溪群（湖南）、双桥山群（赣北—皖南）、上溪群（皖南）、溪口岩群（皖南—赣东北）、梵净山群（黔东北）和四堡群（桂北）等为代表，发育尖楞褶皱、倾竖褶皱、紧闭倒转褶皱等；上部地层包括从板溪群、丹洲群等以来的地层，产状平缓，褶皱宽缓（见安徽、江西、湖南、广西、贵州等各省/区区域地质志）[2,9,13]。近年来的年代学工作相继证实了该代表性的区域不整合面时代可能在820 Ma左右或者介于ca. 820~815 Ma。在扬子地块北缘的大洪山地区表现出类似的情况，出露的地层有中元古代晚期的打鼓石群与新元古代花山群下段洪山寺组均存在明显的褶皱变形，而花山群上段地层六房咀组变形较弱，暗示了该地区存在新元古代中期的构造挤压过程，对应了增生汇聚作用（ca. 830~810 Ma）[90]。

此外，在攀西—汉南杂岩带中出露的新元古代深部地壳变质岩（包括混合岩和片麻岩等）可能也记录了同变质的变形特征。例如Li *et al.*[29]报道了黄水河群混合岩中发育了同混合岩化的变形，时代在829±23~814±14 Ma，主体的S_1面理平行于原生层理，局部地区的变形S_2褶皱轴面通常呈现东西走向、向南倾斜的产状，暗示了区域上的南向汇聚作用。新元古代同变质的变形作用还需要进一步研究。

4 新元古代长期的大洋俯冲

如前所述，华南陆块在新元古代可能存在多个地体以及广泛的海陆格局，其内部及周缘地区发育宽广的活动陆缘，成为见证汇聚型构造—岩浆—沉积—变质和地体增生事件的场所。综合前人的研究结果，华南板块在新元古代早期以洋内俯冲作用为主（ca. 1 000~900 Ma），随后转变为洋陆俯冲作用为主（ca. 880~810 Ma），并可能持续到了ca. 730 Ma，反映了长时间尺度（>200 Myr）的大洋板片俯冲和增生型造山过程。笔者认为，增生型造山作用能够较好地解释华南新元古代的构造—岩浆和多地体汇聚—拼贴过程，主要证

据有以下三个方面：（1）华南缺少新元古代与大陆碰撞造山有关的高压的蓝片岩—榴辉岩相（变质温压比<10 ℃/km）变质作用，而更多记录了类似地体增生的“软”碰撞作用和俯冲带变质（图4）；（2）华南大陆仅在扬子陆块北部四川盆地地区有着巨厚的岩石圈根（>160 km），而其他地区岩石圈较薄[59-60]，暗示着外部地体向扬子陆块的汇聚缺乏刚性块体的碰撞；（3）扬子陆块的新元古代陆缘造山带以钙碱性岩浆岩为主，伴随着零星出露的较老的洋壳岩石序列、被动陆缘火山—沉积物和外来物质，该岩石组合是增生型造山带的典型特征[86]。

然而，一个比较重要的问题是：为什么华南陆块在新元古代早中期缺乏与大洋板片俯冲作用相关的低温、高压（蓝片岩相和榴辉岩相）变质作用记录，而仅保留了蛇绿岩残片证据？这一方面可能与岩石记录的保存问题有关，蓝片岩和榴辉岩能够出露于地表首先需要一个快速的抬升过程，其次需要一个贫退变质流体的保存环境[91-92]。然而，华南陆块的局部地区可能在 ca. 820~810 Ma经历了从挤压到伸展过程的转换，该过程导致的地温梯度抬升可能促使低温、高压变质岩发生变质叠加改造而未被保存。此外，持续的挤压和陆—陆碰撞环境的缺乏导致蓝片岩和榴辉岩不能够快速抬升至地表。另外一方面，蓝片岩和榴辉岩的缺失可能与新元古代早中期的俯冲还不够冷有关。已有研究表明[93]，在冷俯冲环境下，俯冲板片上的蓝闪石可以保存至240 km深的地区；而在热俯冲环境下，蓝闪石很容易分解，稳定存在于小于40 km深的位置。地球自诞生以来持续地冷却，如果华南新元古代早中期的大洋板片俯冲是热俯冲，那么蓝片岩和榴辉岩将很难以稳定存在。

5 华南新元古代多地体汇聚的资源效应

汇聚大陆边缘是物质和元素循环的核心地带，世界上主要的矿产资源来自汇聚板块边缘[94-95]，不同类型的汇聚边缘（洋—洋俯冲、洋—陆俯冲、陆—陆俯冲和陆—陆碰撞）成矿元素的富集模式不同[95]。中国东南部地区（包括江南造山带和华夏地块）是我国金属矿产的“大粮仓”。其前寒武纪基底毫无疑问为这些金属矿床提供了丰厚的成矿物质基础，是中生代成矿大爆发的“基因”和重要先决条件[96]。但目前来说，对该区的基底如何制约金属成矿尚不清楚。考虑到汇聚型的地体边缘可能作为后期熔体和流体迁移的重要通道，从多地体汇聚角度探讨该区金属成矿作用可能是一个新的思路。

郭令智先生较早将中国东南部地区按照地体的概念划分了16个地体[97]。其后，一些学者把华夏地块沿着政和—大浦断裂划分为东、西华夏地块，它们具有不同的构造特征、岩石组合和地壳演化历史[5,24]，该划分总体为大家所接受。而西华夏地块内部又可以根据基

底差异划分为北侧的武夷地体和南侧的南岭—云开地体[23]。近期，Zhang *et al.*[98]利用中生代花岗岩和火山岩的锆石Hf同位素大数据，在中国东南部识别出多个不同性质（包括古老的、新生的和过渡的三种类型）的地壳单元，进一步支持了中国东南部可能的多地体格局。在中国东南部的古老地体区域，常产出大型—超大型的W-Sn-Nb-Ta和稀土矿床，其成矿母岩可能为先存地壳岩石，由于地壳再造作用释放出成矿流体[98]；而在新生地壳区，常产出Cu-Au矿，其成矿母岩可能为新生的地壳物质，新生地壳物质的再造促进硫化物分解并释放Cu和Au进入埃达克质岩浆，埃达克质岩浆在浅部就位形成斑岩型矿床[98-99]。

值得注意的是，不少金属成矿位于地体结合部位，如湘南、赣南的W-Sn矿和稀土矿，主要位于南岭—云开地体和武夷地体的结合部位；赣东北的W矿和Cu-Au矿，处于扬子地块东南缘与怀玉地体的结合部位；而东南沿海的Cu-Au等一些矿产，主要沿着东、西华夏的界线分布。少量的新元古代锡铌钽小矿床被报道于江南造山带上[100]，也属于块体的边缘。总体来看，块体的边缘一方面有利于深部地幔物质上涌，提供了充分的热量给上覆的新生的或者古老或者具有过渡特征的地壳物质，同时也可能释放流体。而早期的块体边缘很可能具有相对较厚的地壳，这就有利于岩浆的产生和长距离的分异，使得成矿元素在熔体分异和流体迁移的过程中双受益。这些前期的新元古代的多地体汇聚作用可能为成矿流体和熔体运移提供了通道，在熔体上又贡献了成矿元素的初始富集，因此在中国东南部的晚中生代成矿“大爆发”提供了便利。

6 结论

（1）华南板块及其周边地区在新元古代早中期可能存在广泛的洋陆格局和多个地体。

（2）华南板块记录了新元古代长期的大洋—大洋岩石圈和大洋—大陆岩石圈的相互作用以及相关的物质循环、俯冲带岩浆和变质记录、地体增生、构造变形等活动陆缘地壳演化过程。该时期的地体增生—汇聚作用可能较早以北扬子为汇聚中心，随后由于地体拼贴主动大陆边缘的向外迁移而扩张，大陆不断增生，最终造就了华南现今的大体格局。

（3）华南陆块新元古代早中期的多地体汇聚过程为矿产资源形成奠定了物质和结构基础，从新元古代基底的地体边界角度探讨流体和熔体成矿是将来研究的一个新思路。

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参考文献（References）

[1] Zhao G C, Cawood P A. Precambrian geology of China[J]. Precambrian Research, 2012, 222-223: 13-54.

[2] 舒良树. 华南构造演化的基本特征[J]. 地质通报，2012，31（7）：1035-1053. [Shu Liangshu. An analysis of principal features of tectonic evolution in South China Block[J]. Geological Bulletin of China, 2012, 31(7): 1035-1053.]

[3] 张国伟，郭安林，王岳军，等. 中国华南大陆构造与问题[J]. 中国科学（D 辑）：地球科学，2013，43（10）：1553-1582. [Zhang Guowei, Guo Anlin, Wang Yuejun, et al. Tectonics of South China continent and its implications[J]. Science China (Seri. D): Earth Sciences, 2013, 43(10): 1553-1582.]

[4] Shu L S, Yao J L, Wang B, et al. Neoproterozoic plate tectonic process and Phanerozoic geodynamic evolution of the South China Block[J]. Earth-Science Reviews, 2021, 216: 103596.

[5] Lin S F, Xing G F, Davis D W, et al. Appalachian-style multi-terrane Wilson cycle model for the assembly of South China[J]. Geology, 2018, 46(4): 319-322.

[6] Wang L J, Lin S F, Xiao W J. Yangtze and Cathaysia blocks of South China: Their separate positions in Gondwana until early Paleozoic juxtaposition[J]. Geology, 2023, 51(8): 723-727.

[7] Zhao J H, Yang T, Wang W. Orogenic belt resulting from ocean-continent collision[J]. Geology, 2022, 50(11): 1266-1269.

[8] 舒良树，施央申，郭令智，等. 江南中段板块-地体构造与碰撞造山运动学[M]. 南京：南京大学出版社，1995：1-174. [Shu Liangshu, Shi Yangshen, Guo Lingzhi, et al. Plate tectonic evolution and the kinematics of collisional orogeny in the Middle Jiangnan, Eastaren China[M]. Nanjing: Nanjing University Press, 1995: 1-174.]

[9] Wang X L, Zhou J C, Griffin W L, et al. Detrital zircon geochronology of Precambrian basement sequences in the Jiangnan orogen: Dating the assembly of the Yangtze and Cathaysia blocks[J]. Precambrian Research, 2007, 159(1/2): 117-131.

[10] Wang X L, Zhou J C, Griffin W L, et al. Geochemical zonation across a Neoproterozoic orogenic belt: Isotopic evidence from granitoids and metasedimentary rocks of the Jiangnan orogen, China[J]. Precambrian Research, 2014, 242: 154-171.

[11] Zhao J H, Zhou M F, Yan D P, et al. Reappraisal of the ages of Neoproterozoic strata in South China: No connection with the Grenvillian orogeny[J]. Geology, 2011, 39(4): 299-302.

[12] Zhao G C. Jiangnan Orogen in South China: Developing from divergent double subduction[J]. Gondwana Research, 2015, 27(3): 1173-1180.

[13] Yao J L, Cawood P A, Shu L S, et al. Jiangnan orogen, South China: a ~970-820 Ma Rodinia margin accretionary belt[J]. Earth-Science Reviews, 2019, 196: 102872.

[14] Xia Y, Xu X S, Niu Y L, et al. Neoproterozoic amalgamation between Yangtze and Cathaysia blocks: The magmatism in various tectonic settings and continent-arc-continent collision[J]. Precambrian Research, 2018, 309: 56-87.

[15] Gao S, Ling W L, Qiu Y M, et al. Contrasting geochemical and Sm-Nd isotopic compositions of Archean metasediments from the Kongling high-grade terrain of the Yangtze craton: Evidence for cratonic evolution and redistribution of REE during crustal anatexis[J]. Geochimica et Cosmochimica Acta, 1999, 63(13/14): 2071-2088.

[16] Zhang S B, Zheng Y F, Wu Y B, et al. Zircon U-Pb age and Hf-O isotope evidence for Paleoproterozoic metamorphic event in South China[J]. Precambrian Research, 2006, 151(3/4): 265-288.

[17] Yu J H, O'Reilly S Y, Zhou M F, et al. U–Pb geochronology and Hf–Nd isotopic geochemistry of the Badu Complex, Southeastern China: Implications for the Precambrian crustal evolution and paleogeography of the Cathaysia Block[J]. Precambrian Research, 2012, 222-223: 424-449.

[18] Wu Y B, Gao S, Zhang H F, et al. Geochemistry and zircon U–Pb geochronology of Paleoproterozoic arc related granitoid in the Northwestern Yangtze Block and its geological implications[J]. Precambrian Research, 2012, 200-203: 26-37.

[19] Wang W, Zhou M F. Provenance and tectonic setting of the Paleo- to Mesoproterozoic Dongchuan Group in the southwestern Yangtze Block, South China: Implication for the breakup of the supercontinent Columbia[J]. Tectonophysics, 2014, 610: 110-127.

[20] Li J Y, Wang X L, Wang D, et al. Pre-Neoproterozoic continental growth of the Yangtze Block: From continental rifting to subduction–accretion[J]. Precambrian Research, 2021, 355: 106081.

[21] Yu J H, Cai Y F, Sun T, et al. Distribution and enrichment of rare metal elements in the basement rocks of South China: Controls

on rare-metal mineralization[J]. Ore Geology Reviews, 2023, 163: 105797.

[22] 于津海，魏震洋，王丽娟，等. 华夏地块：一个由古老物质组成的年轻陆块[J]. 高校地质学报，2006，12（4）：440-447. [Yu Jinhai, Wei Zhenyang, Wang Lijuan, et al. Cathaysia Block: A young continent composed of ancient materials[J]. Geological Journal of China Universities, 2006, 12(4): 440-447.]

[23] Yu J H, O’Reilly S Y, Wang L J, et al. Components and episodic growth of Precambrian crust in the Cathaysia Block, South China: Evidence from U–Pb ages and Hf isotopes of zircons in Neoproterozoic sediments[J]. Precambrian Research, 2010, 181(1/2/3/4): 97-114.

[24] Xu X S, O’Reilly S Y, Griffin W L, et al. The crust of Cathaysia: Age, assembly and reworking of two terranes[J]. Precambrian Research, 2007, 158(1/2): 51-78.

[25] Li T Z, Jiang M M, Zhao L, et al. Continental fragments in the South China Block: Constraints from crustal radial anisotropy[J]. Journal of Geophysical Research: Solid Earth, 2023, 128(10): e2023JB026998.

[26] Cawood P A, Wang W, Zhao T Y, et al. Deconstructing South China and consequences for reconstructing Nuna and Rodinia[J]. Earth-Science Reviews, 2020, 204: 103169.

[27] Condie K C, Bickford M E, Aster R C et al. Episodic zircon ages, Hf isotopic composition, and the preservation rate of continental crust[J]. Geological Society of America Bulletin, 2011, 123(5/6): 951-957.

[28] Wang H Z, Oscar L, Zhang H F, et al. Recognition and significance of *c*. 800 Ma Upper amphibolite to granulite facies metamorphism in metasedimentary rocks from the NW margin of the Yangtze Block[J]. Journal of the Geological Society, 2020, 177(2): 424-441.

[29] Li J Y, Tang M, Lee C T A, et al. Rapid endogenic rock recycling in magmatic arcs[J]. Nature Communications, 2021, 12(1): 3533.

[30] Li Z M G, Chen Y C, Zhang Q W L, et al. U-Pb dating of metamorphic monazite of the Neoproterozoic Kang-Dian Orogenic Belt, southwestern China[J]. Precambrian Research, 2021, 361: 106262.

[31] Li Z M G, Chen Y C, Zhang Q W L, et al. *P-T* conditions and timing of metamorphism of the Yuanmou area, southern Neoproterozoic Kang-Dian Orogenic Belt, southwest China[J]. Precambrian Research, 2022, 374: 106642.

[32] Zhu Y, Lai S C, Xie W L, et al. Wet calc-alkaline magmatic fractionation in the Middle−Upper crustal sections of the continental arc: Insights from the Neoproterozoic Nanba intrusive complex, western Yangtze Block, South China[J]. GSA Bulletin, 2024, 136(3/4): 928-948.

[33] He Y, Wu Y B, Zhao Y J, et al. Neoproterozoic amphibolite-facies metamorphism of the Douling complex in the northern Yangtze Craton and its tectonic implications: Constraints from petrology and zircon U-Pb-Hf-O isotopes[J]. Precambrian Research, 2023, 390: 107039.

[34] Zhang S B, Zheng Y F, Zhao Z F, et al. Neoproterozoic anatexis of Archean lithosphere: Geochemical evidence from felsic to mafic intrusions at Xiaofeng in the Yangtze Gorge, South China[J]. Precambrian Research, 2008, 163(3/4): 210-238.

[35] Zhao J H, Zhou M F, Zheng J P, et al. Neoproterozoic tonalite and trondhjemite in the Huangling complex, South China: Crustal growth and reworking in a continental arc environment[J]. American Journal of Science, 2013, 313(6): 540-583.

[36] 谷志东，张维，袁苗. 四川盆地威远地区基底花岗岩锆石 SHRIMP U-Pb 定年及其地质意义[J]. 地质科学，2014，49（1）：202-213. [Gu Zhidong, Zhang Wei, Yuan Miao. Zircon SHRIMP U-Pb dating of basal granite and its geological significance in Weiyuan area of Sichuan Basin[J]. Chinese Journal of Geology, 2014, 49(1): 202-213.]

[37] He D F, Li D, Li C X, et al. Neoproterozoic rifting in the Upper Yangtze continental block: Constraints from granites in the Well W117 borehole, South China[J]. Scientific Reports, 2017, 7(1): 12542.

[38] Zheng Y F, Wu R X, Wu Y B, et al. Rift melting of juvenile arc-derived crust: Geochemical evidence from Neoproterozoic volcanic and granitic rocks in the Jiangnan Orogen, South China[J]. Precambrian Research, 2008, 163(3/4): 351-383.

[39] Dong Y P, Hui B, Sun S S, et al. Neoproterozoic tectonic evolution and proto-Basin of the Yangtze Block, China[J]. Earth-Science Reviews, 2024, 249: 104669.

[40] Li J Y, Wang X L, Cawood P A, et al. Neoproterozoic low-*T/P* metamorphism in the Yangtze Block manifests a long-lived subduction girdle around Rodinia[J]. Earth and Planetary Science Letters, 2024, 634: 118678.

[41] Sobolev S V, Brown M. Surface erosion events controlled the evolution of plate tectonics on Earth[J]. Nature, 2019, 570(7759): 52-57.

[42] Tang M, Chu X, Hao J H, et al. Orogenic quiescence in Earth’s Middle age[J]. Science, 2021, 371(6530): 728-731.

[43] Spencer C J, Mitchell R N, Brown M. Enigmatic mid-Proterozoic orogens: Hot, thin, and low[J]. Geophysical Research Letters, 2021, 48(16): e2021GL093312.

[44] Cawood P A, Hawkesworth C J. Earth’s Middle age[J]. Geology, 2014, 42(6): 503-506.

[45] Stern R J. The evolution of plate tectonics[J]. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2018, 376(2132): 20170406.

[46] Stern R J. The Mesoproterozoic single-lid tectonic episode: Prelude to modern plate tectonics[J]. GSA Today, 2020, 30(12): 4-10.

[47] Brown M, Kirkland C L, Johnson T E. Evolution of geodynamics since the Archean: Significant change at the dawn of the Phanerozoic[J]. Geology, 2020, 48(5): 488-492.

[48] Cawood P A, Chowdhury P, Mulder J A, et al. Secular evolution of continents and the Earth system[J]. Reviews of Geophysics, 2022, 60(40): e2022RG000789.

[49] Li Z X, Bogdanova S V, Collins A S, et al. Assembly, configuration, and break-up history of Rodinia: A synthesis[J]. Precambrian Research, 2008, 160(1/2): 179-210.

[50] Cawood P A, Strachan R A, Pisarevsky S A, et al. Linking collisional and accretionary orogens during Rodinia assembly and breakup: Implications for models of supercontinent cycles[J]. Earth and Planetary Science Letters, 2016, 449: 118-126.

[51] Merdith A S, Collins A S, Williams S E, et al. A full-plate global reconstruction of the Neoproterozoic[J]. Gondwana Research, 2017, 50: 84-134.

[52] Wang C, Mitchell R N, Murphy J B, et al. The role of megacontinents in the supercontinent cycle[J]. Geology, 2021, 49(4): 402-406.

[53] Cawood P A, Martin E L, Murphy J B, et al. Gondwana’s interlinked peripheral orogens[J]. Earth and Planetary Science Letters, 2021, 568: 117057.

[54] Zhao J H, Pandit M K, Wang W, et al. Neoproterozoic tectonothermal evolution of NW India: Evidence from geochemistry and geochronology of granitoids[J]. Lithos, 2018, 316-317: 330-346.

[55] Ge R F, Zhu W B, Wilde S A, et al. Neoproterozoic to Paleozoic long-lived accretionary orogeny in the northern Tarim Craton[J]. Tectonics, 2014, 33(3): 302-329.

[56] Konopásek J, Janoušek V, Oyhantçabal P, et al. Did the circum-Rodinia subduction trigger the Neoproterozoic rifting along the Congo–Kalahari Craton margin?[J]. International Journal of Earth Sciences, 2018, 107(5): 1859-1894.

[57] Wang W, Cawood P A, Zhou M F, et al. Low‐δ^{18}O rhyolites from the Malani igneous suite: A positive test for South China and NW India linkage in Rodinia[J]. Geophysical Research Letters, 2017, 44(20): 10298-10305.

[58] Peng M, Wu Y B, Wang J, et al. Paleoproterozoic mafic dyke from Kongling terrain in the Yangtze Craton and its implication[J]. Chinese Science Bulletin, 2009, 54(6): 1098-1104.

[59] An M J, Shi Y L. Lithospheric thickness of the Chinese continent[J]. Physics of the Earth and Planetary Interiors, 2006, 159(3/4): 257-266.

[60] Li M K, Song X D, Li J T, et al. Crust and Upper mantle structure of East Asia from ambient noise and earthquake surface wave tomography[J]. Earthquake Science, 2022, 35(2): 71-92.

[61] Hu P Y, Zhai Q G, Wang J, et al. The Shimian ophiolite in the western Yangtze Block, SW China: Zircon SHRIMP U-Pb ages, geochemical and Hf-O isotopic characteristics, and tectonic implications[J]. Precambrian Research, 2017, 298: 107-122.

[62] Deng H, Peng S B, Polat A, et al. Neoproterozoic IAT intrusion into Mesoproterozoic MOR Miaowan Ophiolite, Yangtze Craton: Evidence for evolving tectonic settings[J]. Precambrian Research, 2017, 289: 75-94.

[63] Wang X S, Gao J, Klemd R, et al. Early Neoproterozoic multiple arc–back-arc system Formation during subduction–accretion processes between the Yangtze and Cathaysia blocks: New constraints from the supra-subduction zone NE Jiangxi ophiolite (South China)[J]. Lithos, 2015, 236-237: 90-105.

[64] Zhang C L, Zou H B, Zhu Q B, et al. Late Mesoproterozoic to early Neoproterozoic ridge subduction along southern margin of the Jiangnan Orogen: New evidence from the Northeastern Jiangxi Ophiolite (NJO), South China[J]. Precambrian Research, 2015, 268: 1-15.

[65] 李怀坤，田辉，周红英，等. 扬子克拉通北缘大洪山地区打鼓石群与神农架地区神农架群的对比：锆石 SHRIMP U-Pb 年龄及 Hf 同位素证据[J]. 地学前缘，2016，23（6）：186-201. [Li Huaikun, Tian Hui, Zhou Hongying, et al. Correlation between the Dagushi Group in the Dahongshan area and the Shennongjia Group in the Shennongjia area on the northern margin of the Yangtze Craton: Constraints from zircon U-Pb ages and Lu-Hf isotopic systematics[J]. Earth Science Frontiers, 2016, 23(6): 186-201.]

[66] Li L M, Lin S F, Xing G F, et al. Geochemistry and tectonic implications of Late Mesoproterozoic alkaline bimodal volcanic rocks from the Tieshajie Group in the southeastern Yangtze Block, South China[J]. Precambrian Research, 2013, 230: 179-192.

[67] Wang W, Zhao J H, Zhou M F, et al. Depositional age, provenance characteristics and tectonic setting of the Meso- and Neoproterozoic sequences in SE Yangtze Block, China: Implications on Proterozoic supercontinent reconstructions[J]. Precambrian Research, 2018, 309: 231-247.

[68] Wu P, Zhang S B, Zheng Y F, et al. Amalgamation of South China into Rodinia during the Grenvillian accretionary orogeny: Geochemical evidence from early Neoproterozoic igneous rocks in the northern margin of the South China block[J]. Precambrian Research, 2019, 321: 221-243.

[69] Shi Y R, Liu D Y, Zhang Z Q, et al. SHRIMP zircon U-Pb dating of gabbro and granite from the Huashan ophiolite, Qinling orogenic belt, China: Neoproterozoic suture on the northern margin of the Yangtze craton[J]. Acta Geologica Sinica-English Edition, 2007, 81(2): 239-243.

[70] Li X H, Li W X, Li Z X, et al. Amalgamation between the Yangtze and Cathaysia Blocks in South China: Constraints from SHRIMP U–Pb zircon ages, geochemistry and Nd–Hf isotopes of the Shuangxiwu volcanic rocks[J]. Precambrian Research, 2009, 174(1/2): 117-128.

[71] Li J Y, Wang X L, Gu Z D. Early Neoproterozoic arc magmatism of the Tongmuliang Group on the northwestern margin of the Yangtze Block: Implications for Rodinia assembly[J]. Precambrian Research, 2018, 309: 181-197.

[72] Huang Y, Wang X L, Li J Y, et al. From arc accretion to within-plate extension: Geochronology and geochemistry of the Neoproterozoic magmatism on the northern margin of the Yangtze Block[J]. Precambrian Research, 2023, 395: 107133.

[73] Wu P, Zhang S B, Zheng Y F, et al. The accretion history of the South China Block at its northwest margin in the Neoproterozoic: Records from the Changba Complex in the Mianlue Zone[J]. Precambrian Research, 2021, 352: 106006.

[74] 董云鹏，张国伟，赖绍聪，等. 随州花山蛇绿构造混杂岩的厘定及其大地构造意义[J]. 中国科学（D 辑）：地球科学，1999，29（3）：222-231. [Dong Yunpeng, Zhang Guowei, Lai Shaocong, et al. Determination and their tectonic significance of Huashan ophiolitic mélange in Suizhou[J]. Science China (Seri. D): Earth Sciences, 1999, 29(3): 222-231.]

[75] 胡正祥，毛新武，田望学，等. 扬子陆块北缘大洪山地区发现晋宁期造山带[J]. 中国地质调查，2015，2（2）：33-39. [Hu Zhengxiang, Mao Xinwu, Tian Wangxue, et al. Discovery of the Jinningian Orogenic Belt on the northern Margin of Yangtze Craton in Mountain Dahong[J]. Geological Survey of China, 2015, 2(2): 33-39.]

[76] Von Huene R, Scholl D W. Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental crust[J]. Reviews of Geophysics, 1991, 29(3): 279-316.

[77] Hacker B R, Kelemen P B, Behn M D. Differentiation of the continental crust by relamination[J]. Earth and Planetary Science Letters, 2011, 307(3/4): 501-516.

[78] Sauer K B, Gordon S M, Miller R B, et al. Transfer of metasupracrustal rocks to midcrustal depths in the North Cascades continental magmatic arc, Skagit Gneiss Complex, Washington[J]. Tectonics, 2017, 36(12): 3254-3276.

[79] Ducea M N, Chapman A D. Sub-magmatic arc underplating by trench and forearc materials in shallow subduction systems; A geologic perspective and implications[J]. Earth-Science Reviews, 2018, 185: 763-779.

[80] Isozaki Y. Anatomy and genesis of a subduction-related orogen: A new view of geotectonic subdivision and evolution of the Japanese islands[J]. Island Arc, 1996, 5(3): 289-320.

[81] Foster D A, Gray D R. Evolution and structure of the Lachlan fold belt (Orogen) of eastern Australia[J]. Annual Review of Earth and Planetary Sciences, 2000, 28: 47-80.

[82] DeCelles P G, Ducea M N, Kapp P, et al. Cyclicity in Cordilleran orogenic systems[J]. Nature Geoscience, 2009, 2(4): 251-257.

[83] 张泽明，丁慧霞，董昕，等. 俯冲带变质作用与构造机制[J]. 岩石学报，2021，37（11）：3377-3398. [Zhang Zeming, Ding Huixia, Dong, Xin, et al. Metamorphism and tectonic mechanisms of subduction zones[J]. Acta Petrologica Sinica, 2021, 37(11): 3377-3398.]

[84] 舒良树，周围庆，施央申，等. 江南造山带东段高压变质蓝片岩及其地质时代研究[J]. 科学通报，1993，38（20）：1879-1882. [Shu Liangshu, Zhou Weiqing, Shi Yangshen, et al. High-pressure metamorphic blueschist within the eastern Jiangnan Orogen and its Formation age[J]. Chinese Science Bulletin, 1993, 38(20): 1879-1882.]

[85] Yang Z, Cawood P A, Zi J W, et al. Mid-Neoproterozoic (ca. 845 Ma) metamorphism of the southwestern Yangtze Block and its tectonic implications[J]. Precambrian Research, 2024, 400: 107267.

[86] Cawood P A, Kröner A, Collins W J, et al. Accretionary orogens through Earth history[J]. Geological Society, London, Special Publications, 2009, 318(1): 1-36.

[87] 王孝磊，周金城，陈昕，等. 江南造山带的形成与演化[J]. 矿物岩石地球化学通报，2017，36（5）：714-735. [Wang Xiaolei, Zhou Jincheng, Chen Xin, et al. Formation and Evolution of the Jiangnan Orogen[J]. Bulletin of Mineralogy, Petrology and Geochemistry, 2017, 36(5): 714-735.]

[88] Wang X L, Zhou J C, Wan Y S, et al. Magmatic evolution and crustal recycling for Neoproterozoic strongly peraluminous granitoids from southern China: Hf and O isotopes in zircon[J]. Earth and Planetary Science Letters, 2013, 366: 71-82.

[89] Li J Y, Wang X L, Gu Z D. Petrogenesis of the Jiaoziding granitoids and associated basaltic porphyries: Implications for extensive early Neoproterozoic arc magmatism in western Yangtze Block[J]. Lithos, 2018, 296-299: 547-562.

[90] Huang Y, Wang X L, Li J Y, et al. Early Neoproterozoic tectonic evolution of northern Yangtze Block: Insights from sedimentary sequences from the Dahongshan area[J]. Precambrian Research, 2021, 365: 106382.

[91] Matthews A, Schliestedt M. Evolution of the blueschist and greenschist facies rocks of Sifnos, Cyclades, Greece. A stable isotope study of subduction-related metamorphism[J]. Contributions to Mineralogy and Petrology, 1984, 88(1/2): 150-163.

[92] Avigad D. Tectonic juxtaposition of blueschists and greenschists in Sifnos Island (Aegean Sea)—implications for the structure of the Cycladic blueschist belt[J]. Journal of Structural Geology, 1993, 15(12): 1459-1469.

[93] Bang Y, Hwang H, Kim T, et al. The stability of subducted glaucophane with the Earth’s secular cooling[J]. Nature Communications, 2021, 12(1): 1496.

[94] Pirajno F. A classification of mineral systems, overviews of plate tectonic margins and examples of ore deposits associated with convergent margins[J]. Gondwana Research, 2016, 33: 44-62.

[95] 郑永飞，陈伊翔，陈仁旭，等. 汇聚板块边缘构造演化及其地质效应[J]. 中国科学（D 辑）：地球科学，2022，52（7）：1213-1242. [Zheng Yongfei, Chen Yixiang, Chen Renxu, et al. Tectonic evolution of convergent plate margins and its geological effects[J]. Science China (Seri. D): Earth Sciences, 2022, 52(7): 1213-1242.]

[96] Wang G G, Ni P, Yao J, et al. The link between subduction-modified lithosphere and the giant Dexing porphyry copper deposit, South China: Constraints from high-Mg adakitic rocks[J]. Ore Geology Reviews, 2015, 67: 109-126.

[97] 郭令智，施央申，马瑞士，等. 中国东南部地体构造的研究[J]. 南京大学学报（自然科学版），1984，20（4）：732-739. [Guo Lingzhi, Shi Yangshen, Ma Ruishi, et al. Tectonostratigraphic terranes of southeast China[J]. Journal of Nanjing University (Natural Sciences Edition), 1984, 20(4): 732-739.]

[98] Zhang Z Y, Hou Z Q, Lü Q T, et al. Crustal architectural controls on critical metal ore systems in South China based on Hf isotopic mapping[J]. Geology, 2023, 51(8): 738-742.

[99] Hou Z Q, Pan X F, Li Q Y, et al. The giant Dexing porphyry Cu–Mo–Au deposit in east China: Product of melting of juvenile Lower crust in an intracontinental setting[J]. Mineralium Deposita, 2013, 48(8): 1019-1045.

[100] 向路. 江南造山带西缘新元古代锡铌钽成矿作用[D]. 南京：南京大学，2020：1-199. [Xiang Lu. Neoproterozoic tin-niobium-tantalum metallogenesis in the western part of Jiangnan Orogen[D]. Nanjing: Nanjing University, 2020: 1-199.]

Neoproterozoic Multi-Terrane Convergence in South China and its Resource Implications

LI JunYong[1], WANG XiaoLei[1], GU ZhiDong[2], HUANG Yu[1], WANG GuoGuang[1]

1. School of Earth Sciences and Engineering, Nanjing University, Nanjing, 210023, China

2. Research Institute of Petroleum Exploration and Development, PetroChina, Beijing, 100083, China

Abstract: [Objective] The Neoproterozoic Era marks a crucial period for continental generation, reworking, and reshaping of the South China Block (including the Yangtze Block to the northwest and Cathaysia Block to the southeast). However, Neoproterozoic rocks are widely developed in the block and constitute the leading basement sequences of Phanerozoic rocks and ore deposits. Studying the formation of Neoproterozoic rocks and crustal construction processes of the South China Block is important for exploring regional resources and environment impacts, the assembly and dispersal behaviors of Neoproterozoic supercontinents and the subsequent "Cambrian explosion." **[Methods]** Here, we reviewed key geological records in the South China Block during the Early-to-Middle Neoproterozoic and suggested the existence of a multi-terrane (or multi-microcontinent) structure in South China and nearby regions during the Neoproterozoic. [**Results and conclusions]** This multi-terrane structure may have paved the way for a long-lived ocean-continent interaction in Neoproterozoic South China, as well as consequent arc magmatism, subduction-zone metamorphism, and terrane accretion. Furthermore, the terrane/microcontinent boundaries could be roughly defined by a series active- and passive-continent-margin rock units. Specifically, we speculated the multi-terrane structure was established in the Late Mesoproterozoic and persisted during the Early-to-Middle Neoproterozoic. This conclusion is based on the occurrence of a series of Late Mesoproterozoic to Neoproterozoic oceanic lithosphere relics, including island arc rocks (e.g., Dahongshan, Tongmuliang, Changba, Shuangxiwu arcs) and ophiolites (e.g., Shimian, Miaowan, Huashan, Sanchazi and Northeastern Jiangxi ophiolites). Late Mesoproterozoic continent passive-margin sedimentary rocks (e.g., Shennongjia, Macaoyuan, Kunyang, and Huili Group) that are extensively preserved in the South China Block may correspond to a successful continental rift and support a multi-terrane structure. In the Early Neoproterozoic, we suggest passive continental margins transitioned active ones, and extensive convergent processes operated within the South China Block and its nearby regions. This conclusion is supported: i) linearly-distributed continental-arc calc-alkaline magmatism along western and northern Yangtze margins (i.e., the Panxi-Hannan Belt); ii) rapid endogenic recycling processes induced by ocean-continent subduction recorded in the Huangshuihe migmatites; iii) a range of 880–750 Ma subduction-zone metamorphism reported in the Panxi-Hannan Belt and South Qinling; iv) Neoproterozoic extrusion-related deformation documented within the basement sequences of the Jiangnan Orogen, southeastern Yangtze margins; and v) numerous accretionary rock complexes from the Neoproterozoic that witnessed accretion of oceanic sediments and arcs, ophiolites, outboard terrane (e.g., eastern Jiangnan Orogen, Dahongshan and Huangshuihe Groups, Changba Complex). In this regard, we propose the South China Block experienced a prolonged Neoproterozoic accretionary orogeny and consequent terrane/microcontinent amalgamation, accompanied by possible outward migration and reorganization of active continental margins. These Neoproterozoic subduction-accretion processes played an important role in shaping the current South China Block. More importantly, these Neoproterozoic terrane-boundary domains could be major sites for Phanerozoic crustal differentiation and element recycling that led to the formation of a range of ore deposits within the South China Block. For example, W-Sn and rare earth ores in southern Hunan and southern Jiangxi provinces situate in boundary domains between Nanling-Yunkai and Wuyi terranes. Additionally, W and Cu-Au ores in northeastern Jiangxi province are located at boundary domains between Huaiyu terrane and southeastern Yangtze margin. This potential connection between Neoproterozoic basement and Phanerozoic ore-forming processes requires further investigation in the future.

Key words: South China Block; Neoproterozoic; subduction-accretion; multi-terrane convergence; resource implication