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从板缘碰撞到陆内造山:华南东南缘早古生代造山作用演化

徐亚军[1,2,3],杜远生[1,2,3]
1.中国地质大学地质过程与矿产资源国家重点实验室,湖北武汉　430074
2.中国地质大学生物地质与环境地质国家重点实验室,湖北武汉　430074
3.中国地质大学地球科学学院,湖北武汉　430074

摘要:华南的广西运动被认为是发生在早古生代的陆内造山作用,然而触发陆内变形的地球动力学机制仍然不清.广西运动形成了泥盆系与下伏岩石之间广泛的不整合面以及分布在局部地区的下古生界内部的多个不整合面.广西运动期间的构造热事件和古生物响应时间在460～380 Ma,时间上对应于奥陶系和泥盆系之间的多个不整合,而分布在华南南缘的寒武系和奥陶系之间的不整合面(郁南运动)仅与少量的530～480 Ma之间的变质事件相当,但是却同步于广泛分布在东冈瓦纳北缘的造山事件.华南南部寒武系－奥陶系不整合面上下的碎屑锆石年代学研究表明,早古生代华南与印度北缘相连,而三亚地块在寒武纪是澳大利亚西缘的一部分,直到奥陶纪才与华南拼合,同步于冈瓦纳最终的聚合.郁南运动之后,华夏板块处于冈瓦纳内部,来自冈瓦纳东缘造山作用的应力向大陆内部传播,在具有弱流变学性质的南华盆地聚集,导致盆地构造反转,触发了广西运动.早古生代的华南经历了从板缘碰撞(郁南运动)到陆内造山(广西运动)的演化过程.

关键词:广西运动;郁南运动;加里东运动;陆内造山作用;华南;构造地质.
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From Periphery Collision to Intraplate Orogeny: Early Paleozoic Orogenesis in Southeastern Part of South China

Xu Yajun[1,2,3], Du Yuansheng[1,2,3]
1.*State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan　430074, China*
2.*State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Wuhan　430074, China*
3.*School of Earth Sciences, China University of Geosciences, Wuhan　430074, China*

Abstract: The Early Paleozoic Kwangsian Orogeny in South China is considered to have resulted from the intraplate deformation. However the geodynamic mechanism for the intraplate deformation remains unclear. The Early Paleozoic orogenesis is marked by a regional unconformity between pre-Devonian and Devonian strata and multiple stratigraphic unconformities developed within the Early Paleozoic sequence in the local areas of southeast South China. The Kwangsian magmatism, metamorphism and palaeontological variation are dated from 460 to 380 Ma. These events are in age linked to the multiple unconformities between the Ordovician and Devonian sequences. The unconformity between the Late Cambrian and Early Ordovician, named as the Yu'nan Event in the southern margin of South China, is lack of contemporaneous petrological records, except for minor metamorphic rocks dated at 530－480 Ma. The range of this unconformity corresponds with timing of orogenic activity extending along the northern margin of East Gondwana. Derivation of detrital zircons from the Cambrian and Ordovician strata in the

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作者简介:徐亚军(1978－),男,副教授,博士,主要从事构造地质学和大地构造沉积学方面的教学和科研工作.ORCID:0000-0002-2487-6272.
E-mail:xuyajun19@163.com

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southern part of South China suggests that in the Cambrian South China constituted part of the north India and the Sanya Block presented currently in Hainan Island had not been part of South China but rather part of western Australia until the juxtaposition of South China and west Australia in the Early Ordovician.The event removed the Cathaysia Block from any spatial association with an active plate boundary and permitted the stresses sourced from the accretionary orogen in East Gondwana to propagate inboard across the supercontinent. These stresses localized along the site of the weak rheological Nanhua basin and consequently resulted in basin inversion and development of the intraplate Kwangsian Orogeny. The Early Paleozoic orogenesis in the southeastern part of South China evolved from periphery collision in the Yu'nan Event to intraplate orogeny in the Kwangsian Orogeny.

Key words:Kwangsian Orogeny; Yu'nan Event; Caledonian Event; intraplate orogeny;South China; tectonic geology.

0 引言

板块构造体制下的陆内造山作用尽管发生在远离板块边缘的板内地区，但是其发生和发展都与板块边缘的造山活动具有密切的关系(Neil and Houseman，1997；Roberts and Houseman，2001；Raimondo *et al*.，2014).比如中亚地区的新生代板内变形远程响应(far-field response)于印度板块和欧亚板块的碰撞(Yin *et al*.，1998；Yang and Liu，2002；Cunningham，2013)，而南美安第斯中段晚新生代陆内变形则受控于太平洋 Nazca 板块向东的平板俯冲(flat-slab subduction)(Ramos *et al*.，2002).这些陆内变形因为发生时间晚，没有经历后期板块的裂解，所以能够容易地从空间上与板块边缘的活动建立联系.但是对于更古老的陆内造山作用，由于受到后期板块裂解、漂移、旋转、再聚合等一系列改造，陆内造山作用和与其相对应的板块边缘造山活动之间的空间关系已经不复存在，因而增加了建立陆内造山作用驱动机制的难度.

华南东南部在早古生代经历了强烈的挤压造山作用，形成了一个巨型的褶皱带.这个构造事件最初由 Ting(1929)命名为“广西运动”，随后不同学者又相继将其称为华南加里东褶皱带(黄汲清，1945；任纪舜，1990)、华南早古生代造山带(Faure *et al*.，2009)或者武夷－云开造山带(Li *et al*.，2010)等.鉴于“广西运动”的命名时间最早，并且近来陈旭等(2010，2012，2014)详细研究了广西运动在华南内部发生和发展的古生物学和岩相学响应过程，因此本文采用“广西运动”一名进行下面的讨论.广西运动的性质是洋盆关闭之后的碰撞造山作用还是陆内造山作用存在较大的争议.一部分学者认为武夷山西缘和云开西缘出露的 450～430 Ma 中－基性岩具有蛇绿岩－岛弧岩浆岩的性质(覃小锋等，2015；彭松柏等，2016a，2016b；Zhang *et al*.，2016)，因此华南加里东期造山作用具有洋壳俯冲－碰撞的造山体制(Guo *et al*.，1989；Jahn *et al*.，1990；马瑞士，2006；易立文等，2014；陈相艳等，2015；Zhang *et al*.，2015，2016)，消减带位于扬子和华夏板块之间(许德如等，2006；彭松柏等，2016a，2016b)或者沿着现今华南东南缘以东(Zhang *et al*.，2015，2016).而另一部分学者认为华南加里东造山带内没有早古生代蛇绿岩带、岛弧火山岩以及 HP 变质岩，早古生代花岗岩主要是强过铝质属性，很少有新生幔源物质参与(Wang *et al*.，2011，2012a).因此造山作用属于陆内造山体制(舒良树等，2008；Li *et al*.，2010；舒良树，2012；Shu *et al*.，2014)，450～430 Ma 的中－基性岩是由造山带伸展垮塌形成(Yao *et al*.，2012；Wang *et al*.，2013b；Zhong *et al*.，2014).上述争议的焦点主要集中在岩石学成因认识上的差异.而从古生物学和地层学以及沉积学来看，从华夏板块到扬子板块之间存在连续的古生态变化(陈旭等，2010，2012，2014)和沉积物转运(Wang *et al*.，2010；Xu *et al*.，2012；Yu *et al*.，2015)，南华系－奥陶系沉积相呈指状交互沉积(李三忠等，2016)，这些证据支持广西运动属于陆内造山体制(陈旭等，2012，2014；张国伟等，2013).但是对于陆内造山体制来讲，面临的新问题是触发这次陆内变形的机制是什么.由于华南在晚古生代－新生代又经历了裂离、漂移、再拼贴等一系列后期的构造改造(Cawood *et al*.，2013；Metcalfe，2013)，致使早古生代陆内造山作用和与其相关的板块边缘构造活动之间已然分离，所以重新恢复两者之间的成因联系是建立、健全华南广西运动陆内变形机制的必要条件.而要建立这种联系，则需要从“定时”和“定位”两个方面恢复广西运动发生之前华南在全球板块格局中所处的位置.(1)定时：根据板缘活动与陆内变形在发生时间上的先后顺序(Aitken *et al*.，2013；Raimondo *et al*.，2014)，限制板缘活动发生的时间；(2)定位：确定广西运动期间华南大陆所处的板块构造位置，

讨论板缘构造活动的性质.本文即是从陆内造山的角度出发,在详细分析华南广西运动变形时间的基础上,结合下古生界内部不整合面发育以及不整合面上下地层物源差异,首先确定与板块边缘构造活动相关的不整合面,其次根据不整合面上下沉积物记录定位华南的板块构造位置,最后综合讨论广西运动作为陆内造山作用的可能成因以及华南早古生代造山作用的演化过程.

1　区域地质概况

华南是由扬子板块和华夏板块在新元古代沿着江绍缝合带碰撞形成(Li *et al*.,2002;Zhou *et al*.,2002;Cawood *et al*.,2013;Wang *et al*.,2013a).在新元古代晚期,随着 Rodinia 超大陆的裂解,华南经历了陆内裂谷阶段的演化,在板块的中、东部和西缘分别形成了南华陆内裂谷和康滇陆内裂谷(图 1),与裂谷作用相关的火成岩和沉积岩充填在盆地内部(Wang and Li,2003).

早古生代沉积岩整合覆盖在华南前寒武系之上(Wang *et al*.,2010;Xu *et al*.,2013).从华夏区到扬子区,岩石组合呈现有规律的变化.在华夏区寒武系—奥陶系主要以碎屑岩为主,志留系大部分缺失,仅在云开以西的钦州—防城港一带及其以南的海南岛分布,岩性主要是一套砂泥岩组合.在华夏区的寒武系—奥陶系中发育大量浅水沉积构造,岩相分析表明寒武纪—奥陶纪时期的华南处于滨浅海沉积环境(舒良树等,2008;Wang *et al*.,2010;舒良树,2012;Xu *et al*.,2012;Shu *et al*.,2014).在扬子区和华夏区的结合部位,寒武系底部主要以半深海—深海相的黑色岩石为主(Pi *et al*.,2013),向上过渡为碳酸盐岩,奥陶系—志留系转变为浅海相的碎屑岩夹碳酸盐岩的岩石组合(Wang *et al*.,2010;Shu *et al*.,2014).而在扬子区寒武系—奥陶系主要是台地相的碳酸盐岩,奥陶系上部有少量的硅质岩、硅质泥岩和凝灰岩,志留系滨浅海相的砂泥岩整合覆盖在早期的岩石之上.整个华南东南部下古生界中保留的古流向资料(如波痕、槽模等)显示了碎屑沉积物由 SE 向 NW 方向搬运(Wang *et al*.,2010;Shu *et al*.,2014).

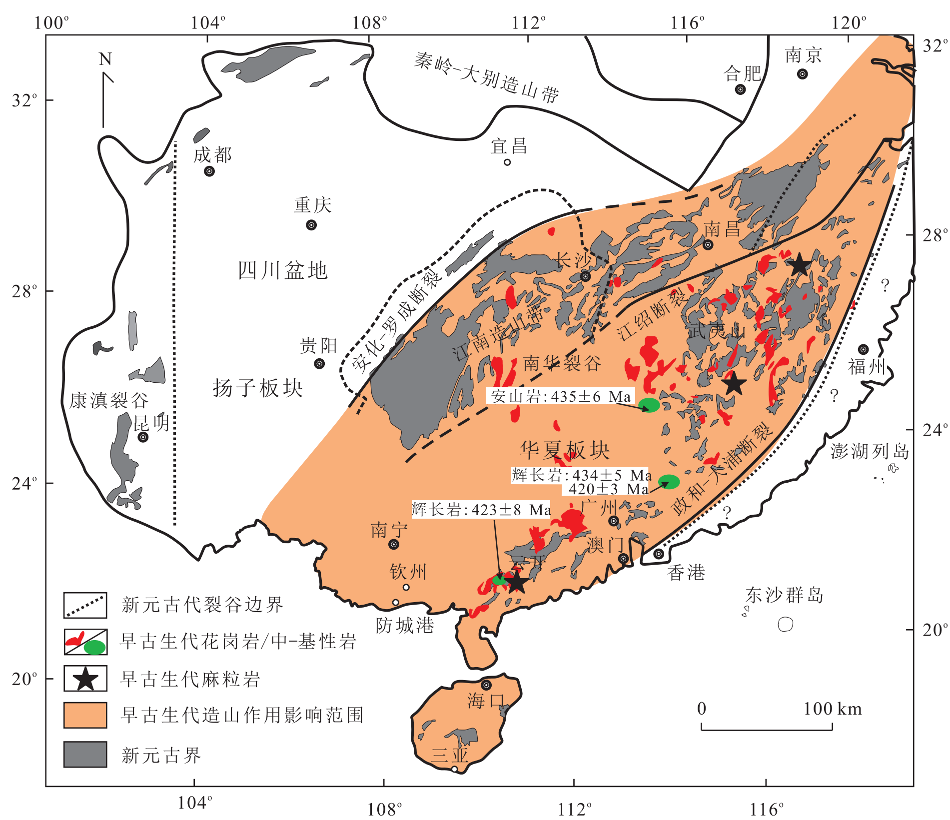

图 1　华南构造单元

Fig.1　Tectonic units of South China

据中国地图,中国地图出版社,2013

早古生代造山作用主要集中在扬子区的安化—罗城断裂和华夏区的政和—大浦断裂之间(Wang *et al.*,2010)(图1),在NE和SW方向上可能分别延伸进入朝鲜半岛(Kwon *et al.*,2006;Kim *et al.*,2014)和印支板块(任纪舜,1990;Carter *et al.*,2001)内部.区内早古生代地层的内部接触关系在时空上呈现不对称性和不等时性.在华南南部云开地区和海南岛,寒武系和奥陶系之间呈平行不整合接触关系,该不整合面被称为郁南运动(莫柱孙等,1980),向北进入华南腹地,接触关系转变为整合接触.奥陶系和志留系之间的接触关系主要见于造山带东南缘的云开地区以及西北缘的雪峰山地区,主要表现为角度不整合,这个不整合面在云开地区被称为北流运动(莫柱孙等,1980),在贵州地区又被称为都匀运动(余开富和王守德,1995).但是在两者之间的地区志留系缺失,泥盆系直接角度不整合覆盖在奥陶系之上、甚至在广西大明山—西大明山一带泥盆系直接覆盖在寒武系之上.在江西等华南腹地奥陶系与泥盆系之间的角度不整合被称为崇余运动(卢华复,1962).从时空关系来看,下古生界内部的不整合面由SE(S)向NW(N)呈现出由老到新的不对称变化(图2),反映了早古生代造山作用由SE(S)向NW(N)方向的发展(陈旭等,2014).伴随着这些不整合面的形成,大量的早古生代花岗岩侵入到早期地层之中.泥盆系底部的砂砾岩不整合覆盖在整个华南的下古生界之上,但是在钦州—防城港一带泥盆系和志留系之间则表现为整合接触关系(广西壮族自治区地质矿产局,1985).

2 华南早古生代造山作用期次及时间

华南东南部不同地区的下古生界内部发育的不整合关系较为复杂(图2),厘清各个不整合面与广西运动之间的成因联系是讨论早古生代造山作用的前提.

近年来的岩石学和古生物学研究从深部过程和浅部响应两个方面很好地约束了广西运动发生的时间和进程.(1)深部过程:①岩浆活动.广西运动导致了分布在扬子区安化—罗城断裂与华夏区政和—大埔断裂之间的大规模花岗岩岩浆侵位以及少量的中基性岩浆活动,花岗岩类型主要为片麻状和块状的S型花岗岩及较少的I型和A型花岗岩,年龄主要集中在460~380 Ma之间(Wang *et al.*,2007,2011,2012a;徐先兵等,2009;Li *et al.*,2010;Liu *et al.*,2010;Wan *et al.*,2010;Yang *et al.*,2010;张菲菲等,2010;王永磊等,2011;张文兰等,2011;程顺波等,2012;Zhang *et al.*,2012a;Zhong *et al.*,2013;Guan *et al.*,2014;Xia *et al.*,2014)(图3);其中,在伸展背景下形成的A型花岗岩和基性岩年龄集中在450~415 Ma,峰期年龄集中在435 Ma左右(Yao *et al.*,2012;Wang *et al.*,2013b;Feng *et al.*,2014;Zhong *et al.*,2014).②变质作用.广西运动经历了顺时针 *P-T* 轨迹的变质作用(Zhao and Cawood,1999;Li *et al.*,2010;Li *et al.*,2011;Chen *et al.*,2012;Wang *et al.*,2012a),变质级别一般达到角闪岩相—绿片岩相,但在武夷山、南岭东段、云开和海南岛等地区也有麻粒岩相变质岩出露(张业明等,1999;于津海等,2005,2007,2014;Wan *et al.*,

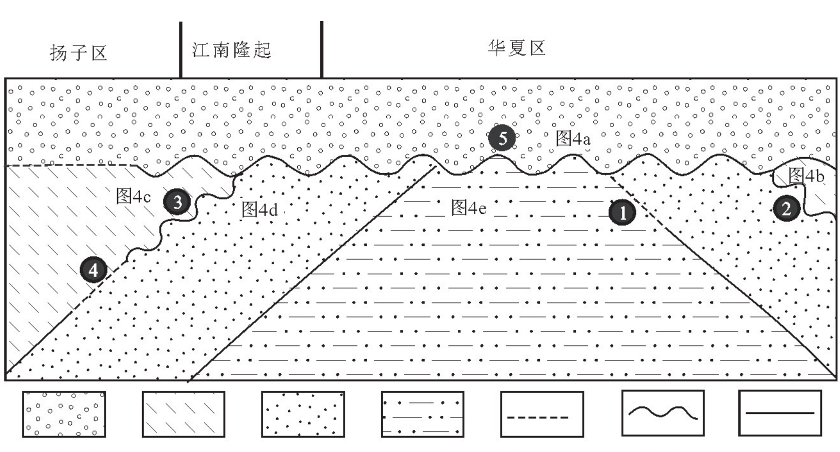

图2 华南东南部下古生界—泥盆系接触关系

Fig.2 Stratigraphic relationship of the Lower Paleozoic-Devonian strata in the southeastern part of South China

1.郁南运动;2.北流运动;3.崇余运动;4.都匀运动;5.广西运动

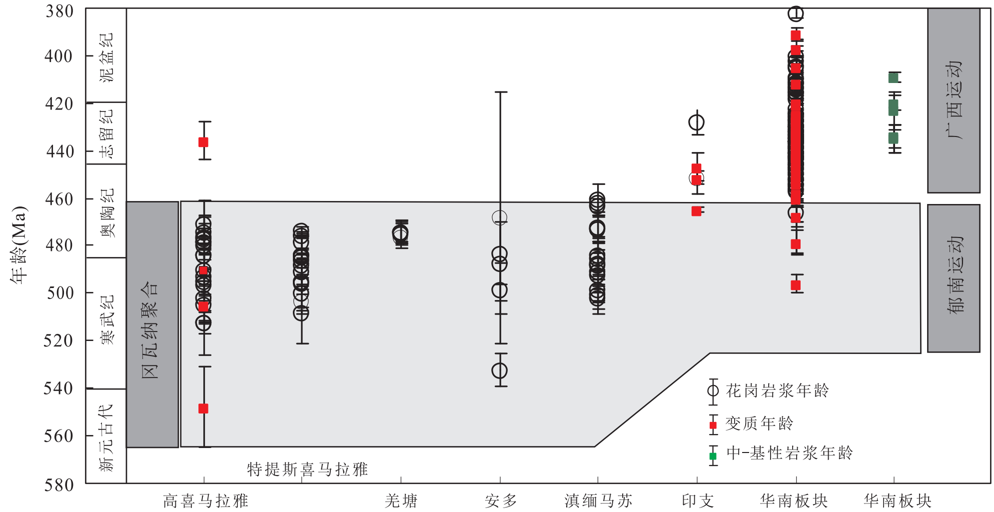

图 3　东冈瓦纳北缘和华南早古生代构造热事件

Fig.3　The Early Paleozoic tectonothermal events in the northern margin of East Gondwana and South China

喜马拉雅、羌塘、安多、滇缅马苏、印支地块数据引自 DeCelles *et al*.(2000)、Lee *et al*.(2000)、Roger *et al*.(2000)、Nagy *et al*.(2001)、Johnson *et al*.(2001)、Catlos *et al*.(2002)、Gehrels *et al*.(2006a,2006b)、Cawood *et al*.(2007)、Lee and Whitehouse(2007)、Liu *et al*.(2007)、Song *et al*.(2007)、Liu *et al*.(2009)、Yin *et al*.(2010b)、Pullen *et al*.(2011)、Guynn *et al*.(2012)、Wang *et al*.(2012a)、Zhang *et al*.(2012b)、Lin *et al*.(2013)和 Wang *et al*.(2013d);华南数据引自舒良树等(1999,2008)、于津海等(2005,2014)、Wang *et al*.(2007,2011)、陈正宏等(2008)、曾雯等(2008)、Faure *et al*.(2009)、徐先兵等(2009)、Charvet *et al*.(2010)、Li *et al*.(2010,2017)、Liu *et al*.(2010)、Wan *et al*.(2010)、Yang *et al*.(2010)、张爱梅等(2010,2011)、张菲菲等(2010)、王永磊等(2011)、Xu *et al*.(2011)、张文兰等(2011)、张苑等(2011)、Chen *et al*.(2012)、Yao *et al*.(2012)、Zhang *et al*.(2012a)、Huang *et al*.(2013)、Wang *et al*.(2012a,2013b,2013c)、王磊等(2013)、Zhao *et al*.(2013)、Zhong *et al*.(2013)、Feng *et al*.(2014)、Guan *et al*.(2014)、Shu *et al*.(2014)、Xia *et al*.(2014)和杨振等(2014)

2007);变质作用的时间主要集中在 450～420 Ma 之间(Liu *et al*.,2010;Li *et al*.,2011;Chen *et al*.,2012;Wang *et al*.,2012a,2013b)(图 3),峰期在 435 Ma左右(于津海等,2005,2007,2014;Wang *et al*.,2012a;Wang *et al*.,2013b;Zhang *et al*.,2015).(2)浅部响应:陈旭等(2010,2012,2014)和戎嘉余等(2010)详细调查了雪峰山东侧广西运动期间生物相和岩相演替的规律,结果表明广西运动存在一个“由南向北”推进的过程,南部地壳抬升发生的时间大致在桑比中期(不晚于 455 Ma;Walker *et al*.,2013),推进到扬子东南缘不早于鲁丹晚期(440 Ma 左右;Walker *et al*.,2013);这一时间段也与广西运动期间岩浆作用和变质作用反映的由挤压向伸展转换的时间一致.由南向北渐进抬升的过程必然导致“南早北晚、南强北弱”的剥蚀,这个可能是泥盆系底部不整合面之下地层由南向北逐渐变新(图 2)的动力学原因.而以往命名的崇余运动面、北流运动面和都匀运动面实际上是广西运动在不同地区、不同阶段的地层记录,应予以合并为统一的“广西运动”.

岩浆作用、变质作用以及古生物学证据限定广西运动发生的时间在沉积上对应于分布在雪峰山以东至政和—大浦断裂以西地区的奥陶系—泥盆系之间的不整合面.而比这个沉积间断更早、分布在华南南部云开—海南岛的寒武系—奥陶系之间的不整合面(郁南运动)则仅有少量的变质年龄(530～480 Ma)与其对应(图 3),表明郁南运动不应归属于陆内造山的广西运动的范畴,因此整个早古生代的造山运动包括了郁南运动和广西运动两期.岩石学和古生物学资料限定了广西运动主要发生在 460～380 Ma,而郁南运动的发生时间则只能通过少量的变质年龄暂时限定在 530～480 Ma.

3　郁南运动的性质

广西运动的驱动机制先后有不同的认识,或者是华南和华北碰撞的远程响应(Wang *et al*.,2007);或者是华南与劳伦大陆拼合的响应(Wu *et al*.,2010;Li *et al*.,2013);亦或是华南与冈瓦纳大陆相互作用的远程响应(Wang *et al*.,2010,2011;李三忠等,2016);再或是在华南以南、现今的南海和东海一带可能曾经存在一个与华南相连的南海地块,该地块向华夏之下的板内俯冲作用导致了广西运动(Shu *et al*.,2014).已有的研究表明广西运动由南向北发展(陈旭等,2012,

2014;杜远生和徐亚军,2012),触发陆内变形的事件应发生在华南南部,显然不支持发生在华南北缘的碰撞(Wang *et al*.,2010).另外,在华南新元古代—早古生代的碎屑岩中,包含了大量 900~550 Ma 的碎屑物质(Wang *et al*.,2010;向磊和舒良树等,2010;Yao *et al*.,2011,2014;Xu *et al*.,2012,2013,2014a;Li *et al*.,2014;Wang *et al*.,2015;Yu *et al*.,2015)(图 4a~4e),这些碎屑物质在劳伦大陆边缘同期沉积物中缺失(图 4g),所以也不支持华南与劳伦大陆相连,而是一致于华南与冈瓦纳大陆(图 4f)之间的相互作用.

奥陶系底部的不整合面广泛分布于东冈瓦纳北缘的地体之上,如喜马拉雅(DeCelles *et al*.,2000;Gehrels *et al*.,2006a,2006b;Cawood *et al*.,2007)、拉萨(李才等,2010)、羌塘(Zhao *et al*.,2014)、Sibumasu(Wang *et al*.,2013d)等,同时伴随着强烈的岩浆侵入和变质作用,年龄集中在 520~470 Ma(图 3).对于该期事件的研究主要集中在喜马拉雅地区,构造机制最初被认为是高喜马拉雅地体向印度北部边缘的增生(DeCelles *et al*.,2000)或者是泛非期造山作用后的伸展(Miller *et al*.,2001),但是从低喜马拉雅地体到高喜马拉雅地体之间新元古代到早古生代连续的沉积以及挤压变形(Gehrels *et al*.,2006a,2006b;Myrow *et al*.,2010;Mckenzie *et al*.,2011)分别与这两种模型不符.Cawood *et al*.(2007)则认为是冈瓦纳聚合后,原特提斯洋洋壳向冈瓦纳北缘下部消减导致安第斯型造山作用,并可能伴随着外部东亚小陆块群向冈瓦纳北缘的增生(Cawood *et al*.,2007;Wang *et al*.,2012b;Wang *et al*.,2013d).

从郁南运动发生的时间来看,其与广西运动应具有某种联系,但是限于华南南部有限的岩石记录,前人对于该期构造活动的研究较少.然而,同期的沉积物中却保存了珍贵的信息.华南南部从新元古代—寒武纪的地层及其保存的碎屑锆石年代学特征与印度北部相似(Jiang *et al*.,2003;Yu *et al*.,2008;Wang *et al*.,2010,2015;向磊和舒良树,2010;Hofmann *et al*.,2011;Yao *et al*.,2011,2014;Xu *et al*.,2013,2014a)(图 4a~4f),表明从新元古代—早古生代华南与印度大陆是相连的.在云开地区,平行不整合覆盖在寒武系之上的奥陶系底部罗洪组砾岩的碎屑锆石年代学和 Hf 同位素调查表明,砾岩中包含有来自喜马拉雅前寒武纪基底的砾石,砾石长轴达 25 cm(Xu *et al*.,2014a).这些资料一方面表明,从新元古代晚期到早古生代华南与印度北缘是

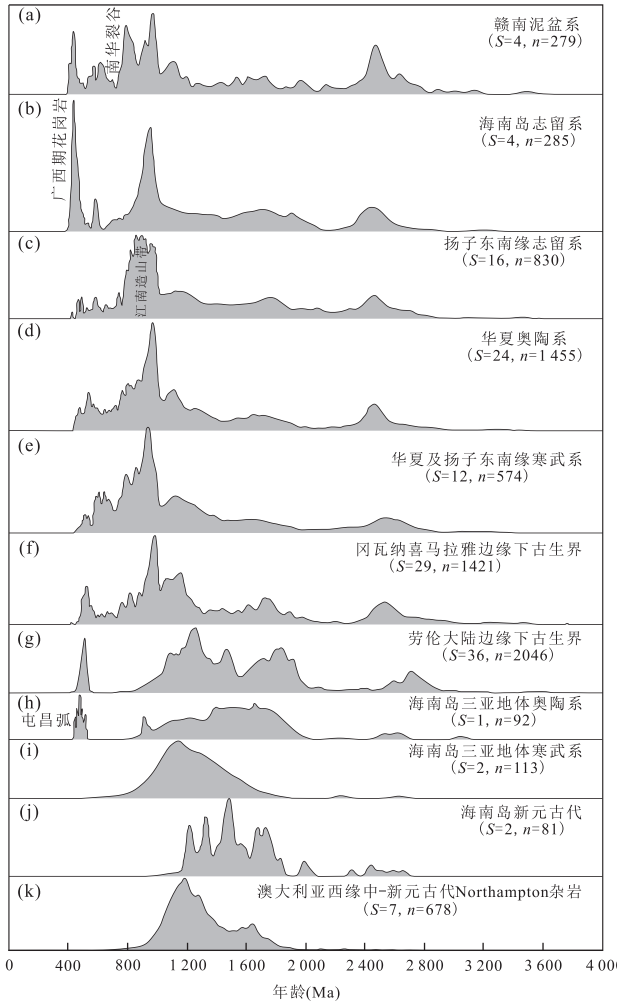

图 4 东冈瓦纳北缘和劳伦大陆边缘早古生代碎屑锆石年龄谱

Fig.4 U-Pb age spectrum of detrital zircons from the Early Paleozoic strata in the northern margin of East Gondwana and Laurentia

注:*S* 为样品件数,*n* 为锆石年龄数.图 a 据向磊和舒良树(2010);图 b 据 Zhou *et al*.(2015);图 c 据 Wang *et al*.(2010)、Xu *et al*.(2012)、Yu *et al*.(2015);图 d 据 Wang *et al*.(2010)、向磊和舒良树(2010)、Yao *et al*.(2011)、Xu *et al*.(2014a)、Wang *et al*.(2014);图 e 据 Xu *et al*.(2013,2014a)、Wang *et al*.(2014);图 f 据 Gehrels *et al*.(2006a,2006b)、McQuarrie *et al*.(2008,2013)、Myrow *et al*.(2009,2010)、Hughes *et al*.(2011)、Long *et al*.(2011);图 g 据 Cawood and Nemchin(2001)、Cawood *et al*.(2003)、Amato and Mack(2012)、Hadlari *et al*.(2012);图 h 据 Xu *et al*.(2014b);图 i 据 Xu *et al*.(2014b);图 j 据 Li *et al*.(2008);图 k 据 Ksienzyk *et al*.(2012)

相连的且距离较近,两者之间并没有洋盆存在,因此安第斯型造山作用模型并不适用于寒武纪—奥陶纪之交、发生在冈瓦纳北缘的造山运动(Xu *et al*.,2014a);另一方面,寒武系—奥陶系之间不整合面以及相关热事件的分布范围指示此次造山事件可能形成了一个喜马拉雅尺度的山链(图 1a),而该不整合

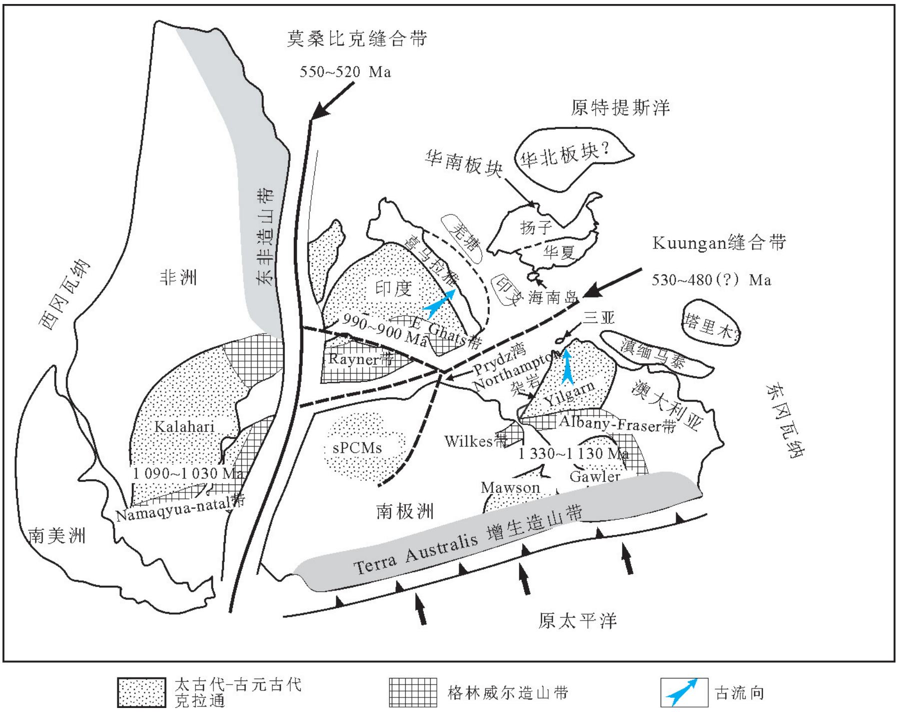

图 5　早古生代冈瓦纳大陆重建

Fig.5　Reconstruction of Gondwana in the Early Paleozoic

据 Boger *et al*.(2001)修改

面的性质从喜马拉雅地区的角度不整合到华南南部的平行不整合、再向北转变为整合接触,说明华南板块可能位于同造山盆地的远端,处在洋-陆转换带上(Xu *et al*.,2014a).海南岛南端三亚地区的寒武纪石英砂岩的碎屑锆石年龄谱和 Hf 同位素组成完全不同于保存在华南大陆同期地层中的碎屑锆石特征,而与澳大利亚西缘的中元古代 Northampton 杂岩一致(Xu *et al*.,2014b)(图 4e,4i,4k);并且 Northampton 杂岩同样也被奥陶系不整合覆盖(Cawood and Nemchin,2000),表明寒武纪三亚地体并不属于华南板块,其很可能与澳大利亚大陆西缘相连.三亚寒武系中保存的三叶虫也支持这一结论(Sun *et al*.,1963).

在海南岛中部屯昌一带保存有寒武纪-奥陶纪的弧火山岩(丁式江等,2002;Xu *et al*.,2007,2008),代表了分隔华南和澳大利亚之间洋盆的一部分.这个洋盆沿着华南东南缘以东,穿过日本(Isozaki *et al*.,2010)和越南北部(Findlay,1997),构成了一条横贯在华南和澳大利亚之间的汇聚大陆边缘(Cock and Torsvik,2013).三亚地区的上奥陶统中保存了来自华南南部琼中地体基底以及屯昌岛弧的碎屑(Xu *et al*.,2014b)(图 4h~4j),说明在晚奥陶世之前三亚地体已经拼贴到了华南南缘.从冈瓦纳北缘的板块格局来看,如果华南和印度北部相连、三亚地体和澳大利亚大陆相连,那么广泛分布在冈瓦纳北缘的寒武纪-奥陶纪之交的造山运动可能代表了冈瓦纳聚合期间澳大利亚和印度板块之间的 Kuunga 碰撞造山事件(Fitzsimons,2000;Boger *et al*.,2001;Meert,2003);碰撞带从南极洲 Prydz 湾向北穿过喜马拉雅东北缘(Chatterjee *et al*.,2007;Yin *et al*.,2010a,2010b)和澳大利亚西缘(Collins,2003),延伸到华南南缘(图 5);郁南运动则是这期碰撞造山事件在华南的表现.在南极洲和澳大利亚,造山作用相关的岩浆和变质作用年龄集中在 550~490 Ma(Fitzsimons,2000;Boger *et al*.,2001;Collin,2003;Meert,2003),而在印度北部和华南南部则集中在 520~470 Ma(Cawood *et al*.,2007;Gehrels *et al*.,2006a,2006b;于津海等,2007;张爱梅等,2011);热事件年龄由南向北变年轻(图 3)说明这个碰撞具有由南向北"斜向碰撞、不规则边缘碰撞"的特点.而华南位于碰撞带的末端,影响微弱,所以在华南没有发生广泛的岩浆和变质作用.

4　广西运动的动力学机制

广西运动的动力学模型先后有不同的观点,如

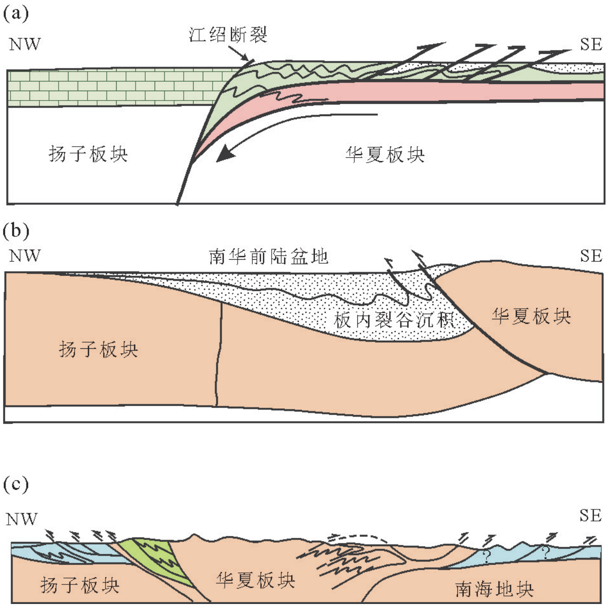

图6　三种建议的广西运动模型

Fig.6　Three proposed models for the Kwangsian Orogeny

a.板内俯冲模型,据Faure *et al*.(2009);b.前陆盆地模型,据Li *et al*.(2010);c.南海地块板内俯冲准对称反转模型,据Shu *et al*.(2014)

华夏沿着江绍断裂的板内俯冲模型(Faure,2009)(图6a)、前陆盆地模型(Li *et al*.,2010)(图6b)、以及南海地块向华夏东南部的板内俯冲而形成的南华裂谷盆地准对称反转模型(Charvet *et al*.,2010;Shu *et al*.,2014)(图6c).

早古生代角闪岩相—麻粒岩相的变质作用主要集中在远离江绍断裂的武夷山和云开两个穹窿区(图1b).沿着江绍断裂的早古生代岩石的变质级别通常为绿片岩相,变质级别的空间变化并不支持沿着江绍断裂发生板内俯冲的模型.前陆盆地模型显示板内变形是由于华南板块和印度北缘在艾迪卡拉纪—奥陶纪早期碰撞,而远程应力一直持续到志留纪(Yao and Li,2016),导致华南陆内变形、华夏向NW仰冲到扬子东南缘(Li *et al*.,2010).然而华南晚前寒武纪—早古生代地层与印度北缘相似(Jiang *et al*.,2003),并且沉积物的物源与印度北缘也具有亲缘性(Yu *et al*.,2008;Cawood *et al*.,2013;Xu *et al*.,2013,2014a,2014b),这些证据表明晚前寒武纪—早古生代华南和印度之间不存在洋盆.况且目前印度北缘报道的岩浆岩年龄老于470 Ma(图3),说明造山作用在中奥陶世之后就已经基本停止,因此不可能在志留纪再向华南板块施加远程应力.

整个华南早古生代地层大致以武夷—云开穹窿一线为轴呈近对称型式分布(图2).地层的碎屑锆石年代学示踪表明,南华盆地基底(包括武夷山基底、新元古代早期江南造山带岩石以及新元古代晚期裂谷火山岩)以及广西期同造山的花岗岩在志留纪快速上隆、剥露,向造山带两侧提供沉积物(Xu *et al*.,2012;Yu *et al*.,2015)(图4b,4c).如此的地层模型和双向沉积物转运方式表明广西运动的造山过程最可能导致南华盆地在晚奥陶世—志留纪沿武夷山—云开一线呈准对称型式隆升,支持其呈准对称正花状构造样式隆升的模型(Charvet *et al*.,2010;Shu *et al*.,2014).

尽管准对称上隆模型强调南海地块的存在以及向华夏板块之下的俯冲,但是驱动南海地块俯冲的动力仍然不明确.陆内造山的驱动力通常源自板块边缘的碰撞力或者消减以及随之产生的山脊地形力向内陆的侧向传递(Roberts and Houseman,2001;Aitken,2011;Raimondo *et al*.,2014),并且陆内变形的时间通常晚于板缘构造事件,比如新生代中亚地区的陆内变形稍晚于印度板块和欧亚大陆之间的碰撞以及青藏高原的隆升(Jolivet *et al*.,2010;Glorie *et al*.,2011;Hu *et al*.,2015).

华南陆内的广西运动启动之前,印度板块和澳大利亚板块在寒武纪—奥陶纪之交碰撞,使冈瓦纳大陆最终聚合(Fitzsimons,2000;Boger *et al*.,2001;Meert,2003;Xu *et al*.,2014b),这个事件是华南南部郁南运动的成因,早于广西运动启动的时间(~460 Ma).然而目前东冈瓦纳北缘报道的构造热事件年龄显示(图3),这次碰撞事件在广西运动启动之前就已终止,并没有与广西运动同步发展,因此碰撞产生的应力对广西运动的形成和发展的影响有限.但是这个事件结束了华南南缘作为板块边缘的演化历史,使华夏板块处于扬子板块和澳大利亚板块之间的陆内构造背景(图5).

陆内造山作用的发展主要受板块边缘构造活动的控制,目前被普遍接受的动力学模型包括平板俯冲和远程效应.郁南运动之后,华南板块构成了东冈瓦纳北缘的一部分,处在洋陆转换带之上(Xu *et al*.,2014a).目前的证据很难确定东冈瓦纳北缘的构造属性属于活动大陆边缘还是被动大陆边缘,主要原因是古特提斯洋的打开和关闭、以及印度板块与欧亚板块在新生代的碰撞可能导致一系列构成东冈瓦纳北缘的地体的裂离,有效的地质证据保留不多.目前东冈瓦纳北缘地体的复原情况表明,与华夏板块邻近的板块边缘位于扬子板块北缘和澳大利亚东缘,扬子板块的北缘面向原特提斯洋(图5).

Wang *et al*.(2007)最早提出华南广西期的陆内变形是华北板块与华南板块之间特提斯洋洋壳双向消减在华北板块南缘和扬子板块北缘之下、之后沿着秦岭造山带碰撞导致的远程效应，但是后来的研究表明扬子板块北缘缺乏与早古生代消减作用相关的岛弧岩浆岩(Wu *et al*.,2009;Dong *et al*.,2013)，早古生代扬子板块的北缘可能并不处于活动大陆边缘的构造背景，因此广西运动远程响应于华北板块和华南板块的碰撞作用就缺乏驱动力.

东冈瓦纳东缘从晚前寒武纪－早中生代(570～230 Ma,Terra Australis 造山带)长期处于原太平洋板块向东冈瓦纳之下消减引起的增生造山作用背景下(Collins,2002;Cawood,2005)，持续的构造活动使得构造应力向东冈瓦纳内部传递、聚集在澳大利亚板块中部，形成了 Alice Springs 陆内造山作用(Raimondo *et al*.,2014).尤其值得注意的是，Alice Springs 造山作用与华南内部广西运动的启动时间同步(图 7)，并且共同经历了 460～400 Ma 的陆内变形过程.而郁南运动之后，华夏板块南缘与澳大利亚板块相接.根据这个时空关系，笔者推断原太平洋和东冈瓦纳之间的增生造山作用形成的应力向冈瓦纳内部传递，不仅聚集在澳大利亚中部，也可能向华南板块传递并聚集在南华盆地内部，引起盆地构造反转，最终导致了广西运动的产生.

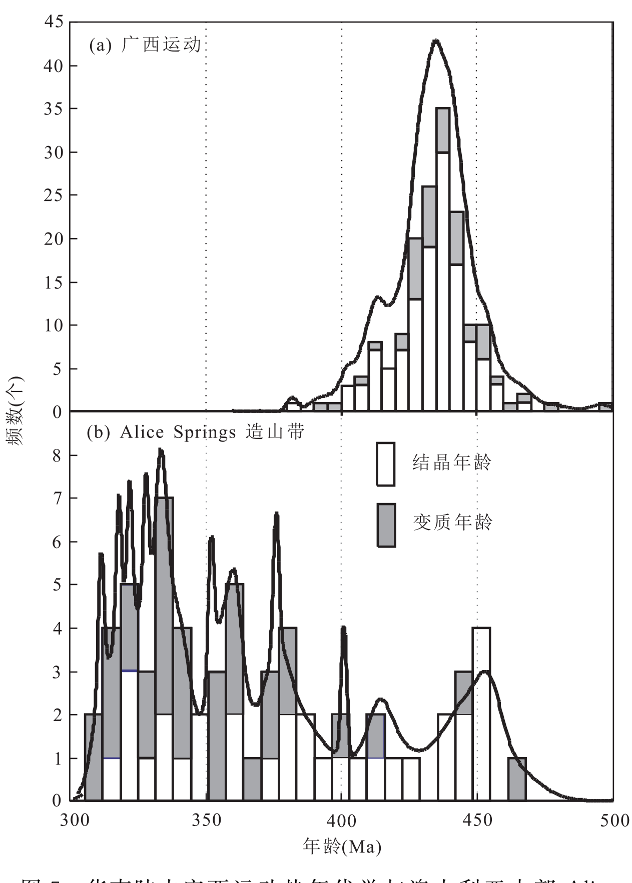

图 7　华南陆内广西运动热年代学与澳大利亚中部 Alice Springs 陆内造山作用热年代学对比

Fig.7　Comparison of tectonothermal events during the intraplate Kwangsian Orogeny in South China and the Alice Springs Orogeny in central Australia

a.广西运动数据来源同图 3;b.Alice Springs 造山带数据引自 Allen and Stubbs(1982)、Dunlap *et al*.(1991)、Cartwright *et al*.(1999)、Hand *et al*.(1999)、Scrimgeour and Raith(2001)、Maidment(2005)、Buick *et al*.(2008)、McLaren *et al*.(2009)、Raimondo *et al*.(2012)和 Maidment *et al*.(2013)

5　华南东南缘早古生代造山作用演化

综上所述，本文认为华南东南缘早古生代的造山作用经历了由板缘碰撞到陆内造山的演化过程(图 8).寒武纪时期，华南板块是冈瓦纳－印度板块北部的一部分，它们与澳大利亚板块之间被 Kuunga 洋盆分割，来自印度北缘和澳大利亚板块的沉积物分别沉积在华南的东南缘和三亚地体之上. Kuunga 洋壳的消减形成了暴露在海南岛中部屯昌一带的岛弧型岩浆岩(丁式江等，2002;Xu *et al*.,2007,2008)(图 8a).洋盆在寒武纪－奥陶纪之交关闭，华南板块和澳大利亚板块碰撞，形成了广泛分布在东冈瓦纳北缘的寒武系和奥陶系之间的不整合面，在华南南缘表现为郁南运动及其南部的东西向构造(图 8b).郁南运动之后，冈瓦纳最终聚合，华南板块和澳大利亚板块拼合在一起，两个板块的边界条件发生变化，来自澳大利亚东缘的增生造山作用应力持续向冈瓦纳内陆传播，聚集在具有弱流变学性质的澳大利亚中部(Raimondo *et al*.,2014)和华南东南部的南华盆地内部(Xu *et al*.,2016).应力在南华盆地聚集并活化了华南基底，产生了分布在华南南部的少量同期变质作用(于津海等，2007;张爱梅等，2011).随着应力的进一步集中，最终导致了地壳由南向北的抬升(陈旭等，2012,2014)以及早期与裂谷作用相关的正断层的反转(Charvet *et al*.,2010;Shu *et al*.,2014).随着变形由南向北传播，奥陶纪晚期到达扬子东南缘，遇到冷的、稳定的扬子板块的阻挡(Zhang *et al*.,2013;Lu *et al*.,2014)，在造成扬子东南缘局部的不均衡上升(如桐梓上升、黔中隆起以及新元古代江南造山带的剥露)(戎嘉余等，2011,2012;Yu *et al*.,2015)的同时，南华盆地被夹持在碰撞带和扬子板块之间，双向的挤压导致南华

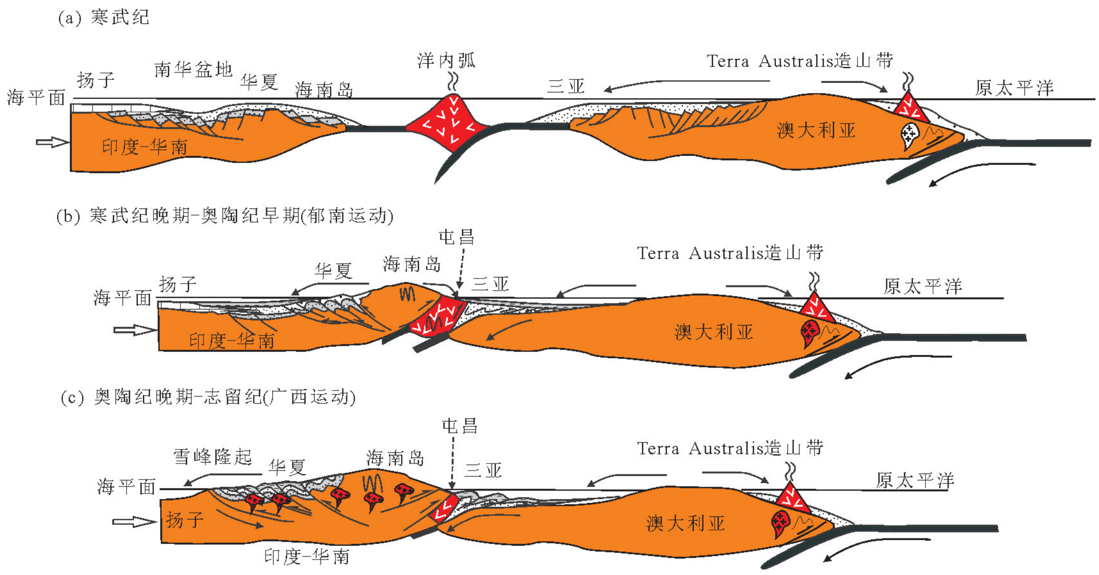

图8　华南东南缘早古生代造山作用演化

Fig.8　The evolution of Early Paleozoic orogenesis in the southeastern part of South China

盆地的全面反转，地壳加厚，早期岩石深埋进入下地壳发生深熔，产生呈面状分布在华南内陆的S型花岗质岩浆和广泛的北东向构造(图8c).挤压作用一直持续到中志留世(435 Ma)，此后向伸展转换，造山带遭受剥蚀夷平.早泥盆世初期，新的海侵由南向北推进，不同层位的泥盆系超覆在整个华南之上，形成泥盆系下部的区域不整合面——广西运动面.因此，华南东南缘早古生代经历了由寒武纪—奥陶纪之交的板缘碰撞造山作用到晚奥陶世—志留纪之间的陆内造山作用的演化过程.

6　存在的问题

尽管近年来华南早古生代的构造演化研究取得了较大进展，但是仍然有几个关键的科学问题需要进一步讨论.

(1)华南东南缘寒武纪—奥陶纪早期(郁南运动之前)活动大陆边缘的进一步厘定.由于政和—大浦断裂以东几乎被中—新生代岩石以及东海和南海海域覆盖，导致在华南东南缘建立活动大陆边缘相当困难，需要更多的来自其他地区的地质资料加以佐证.

(2)早古生代华南东南部是否存在南海地块及其构造属性.造成中亚新生代板内变形的应力是通过处于板内变形带和印度—欧亚碰撞带之间的塔里木板块传播而来.郁南运动是华南直接与澳大利亚板块碰撞导致的还是通过相间的南海地块传递的？即是否存在这样一个中间地块以及它是华南属性还是澳大利亚属性？仍然需要进一步证实.

(3)广西运动结束的时间与钦防海槽的成因.目前变质岩石学研究表明广西运动挤压阶段结束在430 Ma左右，但是与造山作用相关的花岗质岩浆作用一直持续到380 Ma(图3)，这个时间段部分与钦防海槽的扩张期重叠，广西运动准确的结束时间及其如何与板块南缘钦防海槽的扩张相协调等问题需要进一步研究.

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