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南海大陆边缘动力学:从陆缘破裂到海底扩张

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摘　要: 边缘海如何形成是地球科学的基本问题.本研究通过对南海区域深反射地震数据及钻井数据的综合解释,聚焦地壳深部结构和三维全变形机制,在南海陆缘张裂-海盆扩张的构造动力学研究中取得重要进展:(1)"大陆破裂非均一":拉张过程垂向上分层非均一,受拆离断层系统控制;裂离过程横向上高度变化,中-东侧受岩浆作用主导,西侧受构造作用主导.(2)"海盆扩张非对称":受周期性地幔对流活动主导,扩张表现为两次洋脊南向跃迁,方向也发生多次转变,导致南海扩张的不连续-非对称性.据此提出西太俯冲背景下周缘受限型海盆高度变化-非均衡扩张模式的新认识,丰富大陆边缘动力学理论.

关键词: 深反射地震探测;地壳结构;非均一破裂;非对称扩张;南海;海洋地质.

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Continental Margin Dynamics of South China Sea: From Continental Break-Up to Seafloor Spreading

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Abstract: Opening mechanism of marginal basins is one of the fundamental issues of earth science. Based on integrated geological interpretations on deep-reflection seismic and drilling data in the South China Sea (SCS), this study analyzes the deep crustal structure and deformational patterns, the results show: (1) The extension and breakup process of the SCS was ununiform and highly variable, i.e. the continental margin experienced depth-dependent stretching dominated by detachment system, and the breakup process was "a magma-rich" type in the middle-east, but a "magma-poor" one in the west. (2) The spreading process of the SCS was unbalanced and asymmetric, featured with two episodic southward ridge jumps, as well as multiple changes of spreading orientation, resulting in the asymmetric post-spreading magmatism and inhomogeneous lithospheric structure. Base on above-mentioned research, we propose an opening model for tectonic-restricted marginal basins dominated by the West Pacific subduction, which is featured with highly variable continental rifting and ununiform seafloor spreading. The model can enrich the theory of continental margin dynamics.

Key words: deep-reflection seismic exploration; crustal structure; ununiform breakup; asymmetric spreading; South China Sea; marine geology.

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0　引言

大陆边缘动力学是探索大陆边缘从张裂到汇聚之地球动力学过程的学科,也是板块构造理论的重要组成部分.《*Science*》在 2016 年提出了 125 个未知的科学问题,其中在地球科学领域最具挑战性的问题就是地球内部如何运行,即固体地球系统的循环过程.大陆边缘不仅是物质和能量循环的主要场所,也是火山、地震等活动最为密集的区域,是了解固体地球循环的关键(如张培震等,2003;郑永飞等,2015).

经典的板块构造理论主要建立在对大型洋盆海底构造研究的基础上,比如太平洋、大西洋.而对于小型洋盆,由于受到周缘大型板块的构造耦合影响,动力学过程尤为复杂.比如占全球边缘海总量约 75% 的西太平洋边缘海盆,其陆缘张裂到海底扩张是板块俯冲汇聚背景下的拉张过程,与经典的"威尔逊旋回"超级大陆裂解过程相比(如冈瓦纳大陆裂解形成大西洋),具有独特的张裂模式和动力学机制.南海是西太平洋边缘海的典型代表,位于太平洋构造域和印度洋构造域的结合部位,其四周被一系列俯冲带所围限,内部却发生了大陆破裂和海底扩张.这样形成的南海规模小、年龄新,而且具有多变的陆缘类型和复杂的扩张过程,是西太平洋地区具有高度变化特征海盆的典型代表(姚伯初和曾维军,1994;汪品先,2012).对南海"生命史"的研究不仅是西太平洋构造演化和海陆相互作用的关键,也可以丰富和完善目前基于大型洋盆研究的板块构造理论.

自 2002 年以来,笔者基于国家自然科学基金重大计划、国家海洋专项调查、国际合作和国际大洋发现计划(IODP)获取的数据资料和样品分析,开展南海大陆边缘全地壳尺度深部结构、动力过程与构造-沉积响应等研究,探索以南海为代表的西太平洋边缘海盆的生命史,也即"南海陆缘如何破裂"、"海盆如何形成"、"扩张为何停止"等问题,以期深化对西太平洋汇聚背景下边缘海"非稳态不连续"扩张过程的认识,并对以往立足于大型洋盆的大陆边缘动力学理论作出有益的补充.

1　南海"大陆破裂非均一"的拉张-破裂模式

作为板块构造学说精髓的威尔逊旋回,囊括了大型洋盆从发生、发展到衰退、消失的演变过程,而这其中大陆开始拉张,并最终破裂是其中的基石.南海形成历史不长、空间尺度不大,陆缘的变形模式和构造属性相较于大型洋盆(如大西洋)的陆缘具有独特性,是研究周缘受限型小洋盆大陆边缘张裂过程的理想场所.

经典的大陆拉张模型包括对称的纯剪模型(pure shear model)和非对称的单剪模型(simple-shear model)(McKenzie,1978;Wernicke,1981),两者的拉张因子虽在横向上有变化,但纵向上随深度的变化被认为是一致的,为均一模型(图 1c).但对南海南、北陆缘的典型盆地(如南沙地区盆地)构造变形特征分析和拉张因子计算表明,上地壳拉张因子和下地壳拉张因子存在巨大差异(图 1a、1b),也即伸展作用在纵向上是不均匀的,伸展因子随深度发生变化,南海陆缘的拉张为非均一模型(Ding *et al.*, 2013).南海陆缘在大陆裂解初期的伸展作用表现为高角度断层,随着拉张作用的进行,断层逐渐平缓发育成低角度的拆离断层,拆离面在部分区域为上、下地壳界面(丁巍伟和李家彪,2011a;丁巍伟等,2011b;Ding *et al.*, 2016a),或者沿着莫霍面拆离(如 Liang *et al.*, 2019; Li *et al.*, 2020).这种大型拆离构造发育反映了下地壳塑性流动作用的结果,洋壳初始扩张的区域可深至地幔(Clift and Lin, 2001; Davis and Kusznir, 2003,孙珍等,2009; Crosby *et al.*, 2011).

陆缘的持续拉张最终导致大陆破裂.目前地学界基于对大西洋陆缘的研究建立了两个经典陆缘破裂模型:岩浆作用为主导的"富岩浆"型(magma-rich type)和构造伸展为主导的"贫岩浆"型(magma-poor type).前者以下地壳高速层、地壳上部岩浆流形成的向海倾斜反射层、以及狭窄的洋陆过渡带为特征,如南大西洋安哥拉陆缘(Symonds *et al.*, 1998; Franke *et al.*, 2010);后者以弱岩浆活动、发育拆离断层、剥露的岩石圈地幔、较宽的洋陆过渡带为特征,如北大西洋伊比利亚-纽芬兰陆缘(Whitmarsh *et al.*, 2001; Manatschal and Müntener, 2009).南海陆缘在大陆裂谷期岩浆活动较弱,未发现向海倾斜反射层,陆缘拆离断层发育.但深反射/折射地震探测工作却发现了下地壳高速层的存在(如 Nissen *et al.*,1995;Wang *et al.*, 2006;Zhao *et al.*,2010),无法与上述两种经典模型对应,由此南海破裂过程究竟受岩浆作用控制,还是以构造减

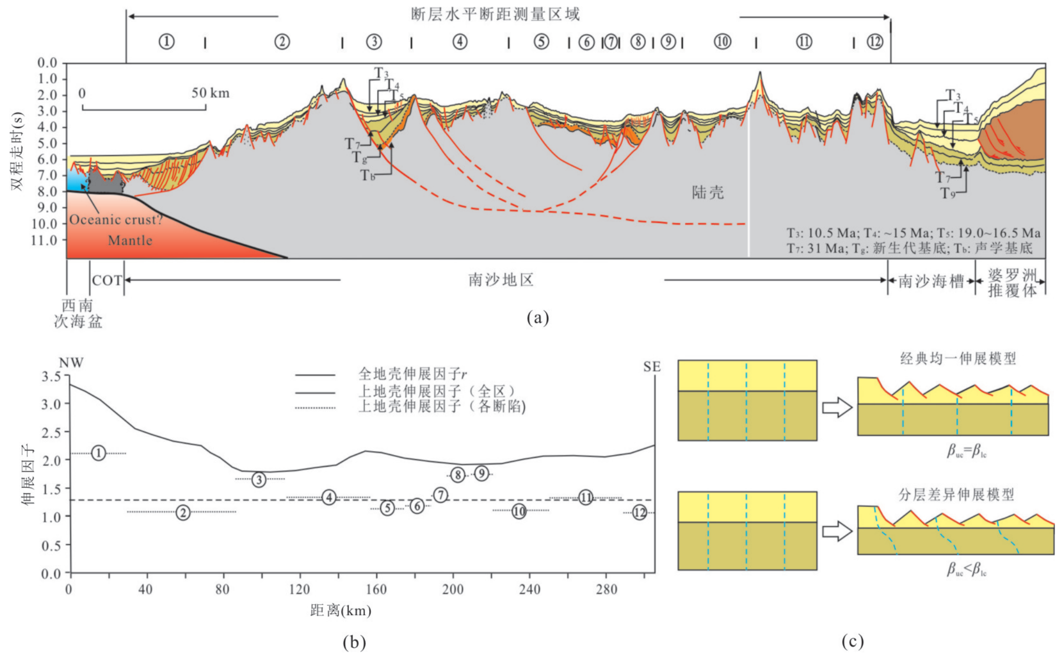

图1 南海南部陆缘的拆离断层构造(a),陆缘地壳拉张因子计算结果(b),经典均一伸展模型和分层差异伸展模型示意(c)

Fig.1 Geological interpretation shows the detachment structures within the southern continental margin of South China Sea (a); calculation results of the continental stretching factors (b); cartoons show the uniform stretching model and ununiform depth-dependent stretching model (c)

图b显示全地壳伸展因子与上地壳伸展因子之间存在巨大差异;图c中亮黄部分为上地壳,暗黄部分为下地壳

薄为主导一直存疑(如姚伯初和万玲,2010; Larsen *et al.*, 2018; Sun *et al.*, 2019; 张远泽等2019).

国际大洋发现计划在2014年进行的IODP 349航次及2017年进行的IODP 367&368航次先后在南海残留扩张脊区及北部洋陆过渡带区进行了钻探,共钻探10个井位.这些钻井不仅确定了南海海盆扩张开始及停止的时间,而且获取了海盆区基底之上新生代沉积的岩性及年代信息(Li *et al.*, 2015; Sun *et al.*, 2018).笔者结合钻探获取的钻井资料,对南海陆缘不同区域的多道地震数据进行了解释,以深入剖析从东侧(东部次海盆)到西侧(西南次海盆)洋陆过渡带区的结构以及大陆破裂—海盆扩张的转换过程,得到以下认识:

(1)南海东部次海盆洋陆过渡带区狭窄(不超过20 km),IODP 367 & 368航次钻遇玄武岩基底,未发现蛇纹石化地幔,与北大西洋伊比利亚“贫岩浆”型模型完全不同(Wang *et al.*, 2019).研究表明洋陆过渡带为“三明治”结构,包括上部岩浆侵入和侧向玄武岩流形成的火成海山—中部的减薄地壳—下部的岩浆底侵层(图2).笔者把这种岩浆增生—构造伸展复合型地质单元解释成“胚胎型”洋壳.在详细分析钻探热流和测井数据的基础上,笔者认为南海中—东部洋陆过渡带由于快速的陆缘拉张,较热的地幔以及塑性下地壳强烈颈缩共同导致岩石圈强烈减薄,软流圈上部发生减压熔融,岩浆熔融物质快速上涌,在大陆拉张的末期形成一期较强烈的岩浆活动(图3a、3b)(Ding *et al.*, 2020).该岩浆活动不仅在洋陆过渡带形成了包括底侵、岩墙侵入等在内的岩浆增生作用,而且使得大陆岩石圈发生破裂,最终导致海底扩张(图3c).虽然在大陆伸展过程中岩浆作用较弱,但南海北部陆缘中—东部的破裂过程并非是前人认为的“贫岩浆”型(如Franke *et al.*, 2014; Brune *et al.*, 2017),而是由较强的岩浆活动为主导.

南海西南次海盆的洋陆过渡带也较为狭窄,但与东部次海盆不同,笔者通过对地震剖面的解释发现西部陆缘洋陆过渡带区莫霍面抬升至近海底,可能指示地幔的出露,并发育大量拆离断层控制的拉张构造,指示着较低的地幔温度和较弱的岩浆作用(Ding *et al.*, 2016b, 2016c).同时在深部结构未发现下地壳高速层(Ding *et al.*, 2012).由此南海西部陆缘的破裂过程中岩浆作用较弱,以构造伸展作用为主,为“贫岩浆”型裂离模式.

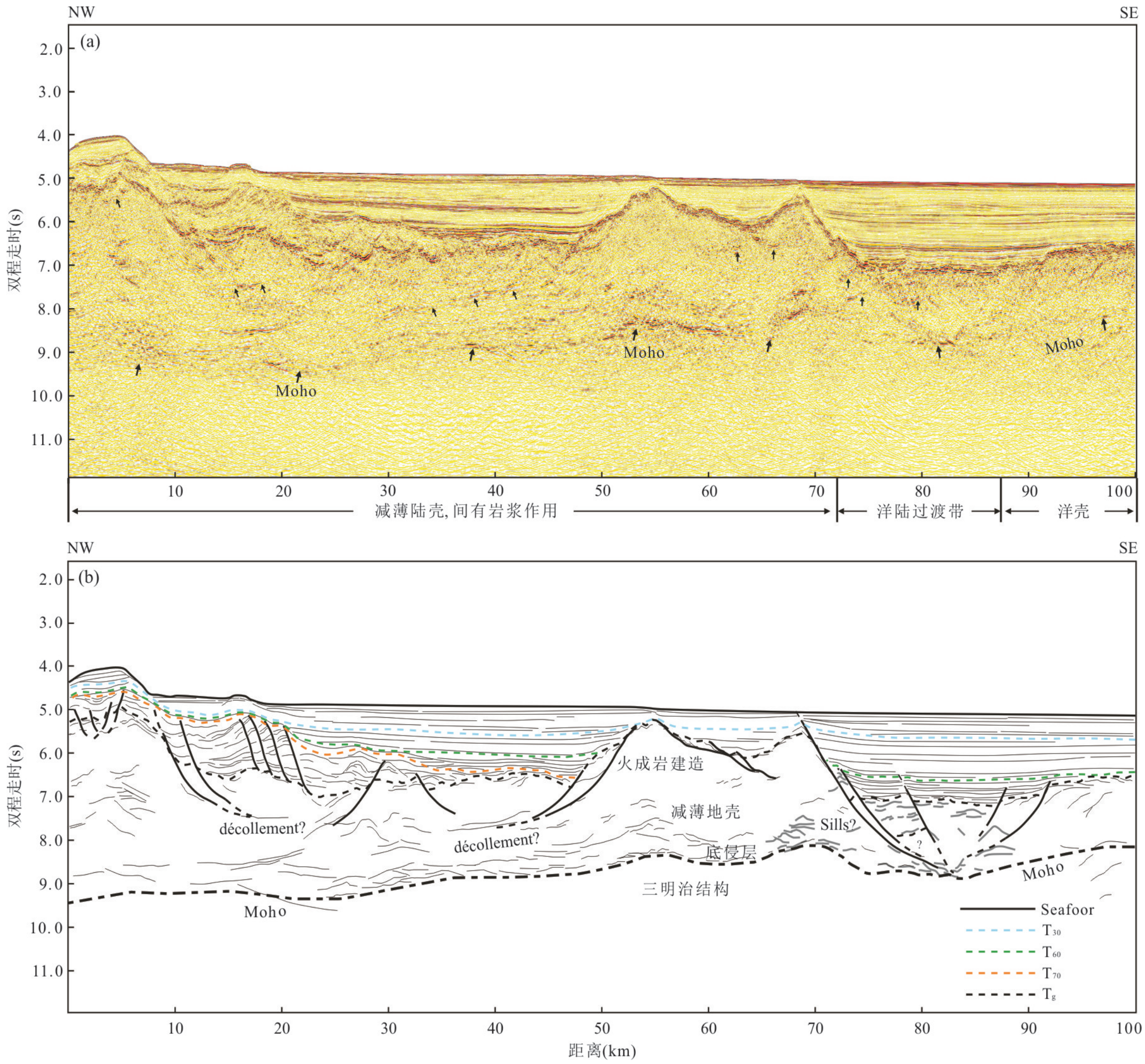

图 2　过南海北部陆缘洋陆过渡带区原始地震剖面(a)及地质解释(b)

Fig.2　Original seismic profile (a) crossing the transitional zone of the northern continental margin of the South China Sea and its geological interpretation (b)

根据南海陆缘非均一分层拉张及复合型破裂的研究成果，笔者建立了以南海为代表的西太平洋边缘海盆独特的陆缘拉张－裂离的模式．南海及周缘区域在中生代期间一直受到古太平洋板块俯冲的作用，使得该区域岩石圈由于长期的俯冲作用变得更“软”更“热”（Sun *et al.*, 2019），尤其是下地壳表现为更多的塑性伸展特征（Zhao *et al.*, 2018）．这种机制与经典的以大西洋为代表的超级大陆板内坚固岩石圈裂解形成大型洋盆的机制相比具有独特性，前者在大陆岩石圈破裂之初就有玄武岩涌出，并很快进入海底扩张状态；而后者需要进行长期拉张使得岩石圈地幔变弱，才最终破裂并出现玄武岩喷涌．

2　南海“海盆扩张非对称”的不均衡扩张模式

板块构造理论的基础之一是海底扩张，即新生洋壳在洋中脊不断的生成．大型洋盆（如大西洋）的洋中脊扩张速度有所变化，如岩浆作用主导的快速扩张，构造拉张主导的慢速、超慢速扩张等（如 White *et al.*, 1990），同时洋中脊会发生局部停止、迁移的现象（如 Barckhausen *et al.*, 2008）．但这些区域扩张过程总体表现为连续的、对称的方式．南海的张开受制于周缘规模巨大的板块（如欧亚板块，太平洋板块等），扩张过程经常被打断，与大西洋等相比记录了更多非稳态特征．对南海洋壳增生和海盆扩张过程、扩张脊不

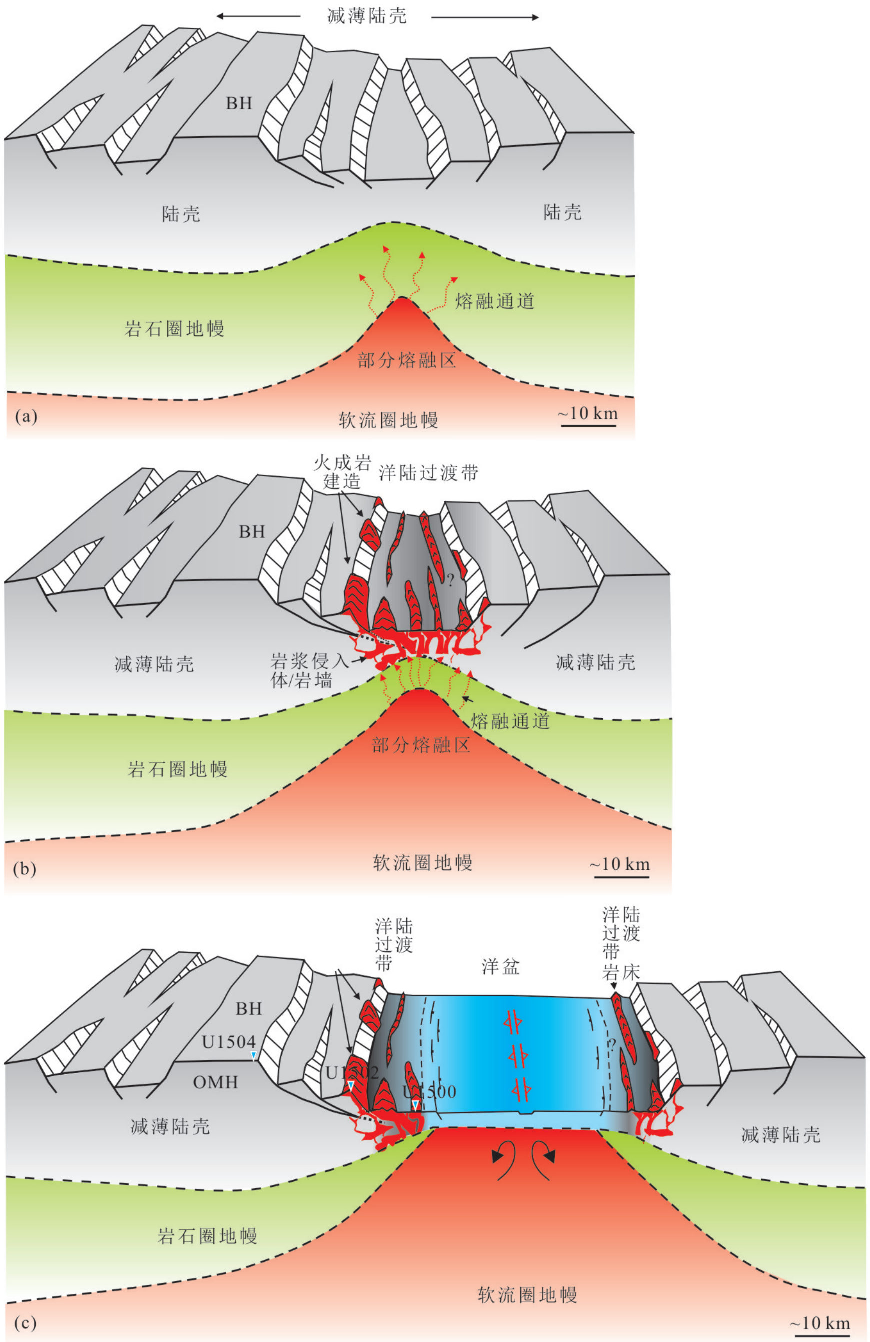

图3　南海北部陆缘东侧大陆破裂-初始海底扩张过程示意

Fig.3　Sketch map shows the process from continental breakup to initial seafloor spreading in the eastern part of the northern continental margin, South China Sea

连续变化控制因素的研究,可以建立边缘海小洋盆不连续扩张、不均一发育的典范.

前人或者通过对磁异常数据的解译(如Briais *et al.*, 1993; Li *et al.*, 2014),或者对海盆线性构造地貌的分析(如李家彪等,2002; Sibuet *et al.*, 2016),均发现南海洋中脊发生过一次向南跃迁的现象,并从地幔热结构差异的角度解释不对称的机制(Zhang *et al.*, 2020).磁力数据和多波束地貌特征容易受到海盆停止后多期强烈岩浆作用的混扰,笔者利用深反射地震数据研究了从洋陆过渡带陆缘至洋中脊(纵向)-沿洋中脊不同区段(横向)洋壳的内部结构、厚度变化和构造变形特征,获得了南海海盆内部结构三维空间变化规律.

大洋的扩张会在深部留下足迹,这些年由于深

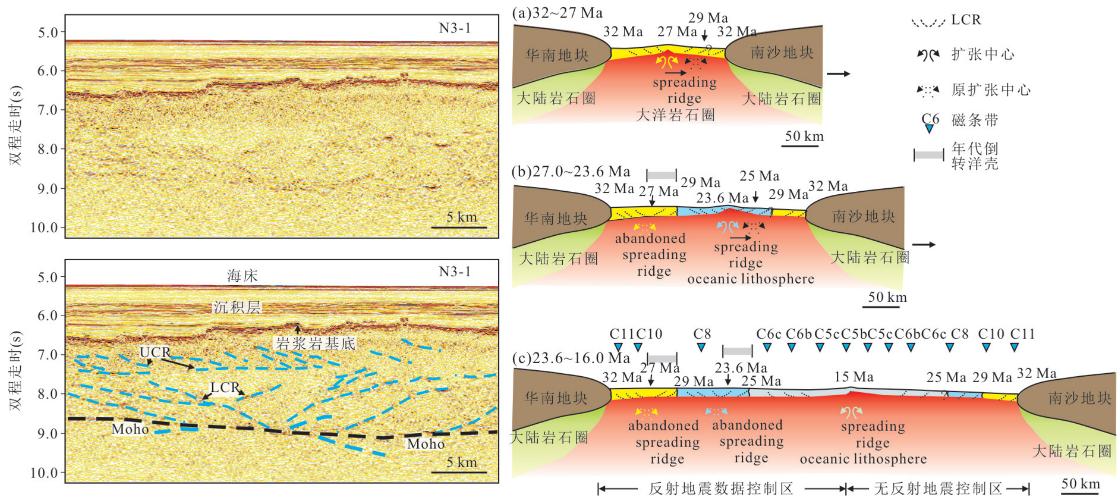

图 4　南海洋壳内部显示的对倾 LCR 构造(左)及洋中脊两次向南跃迁示意(右)

Fig.4　LCR structure within the oceanic crust (left) and two-episodic southward ridge jumps during the seafloor spreading (right), South China Sea

反射地震探测技术的发展,在大洋洋壳内部发现有下地壳反射体(lower crustal reflector,简称 LCR),这种 LCR 终止于莫霍面,倾向普遍朝向洋中脊,在洋中脊两侧形成对称结构(如 Kodaira *et al.*, 2014),是洋壳增生形成过程直接记录的载体,并在包括太平洋、大西洋得到了验证(如 Ranero *et al.*, 1997; White *et al.*, 1990).笔者对南海东部次海盆深反射地震数据所揭示的深部结构研究,发现残留扩张脊北翼洋壳内部存在两组具有对倾的 LCR,明显不同于大型洋盆常见的单倾的 LCR(图 4 左).LCR 的形成机制表明,一组对倾的 LCR 对应一个洋中脊,南海洋盆现今扩张脊北翼有两组对倾的 LCR,说明存在两个残留的扩张脊.由此笔者提出南海扩张脊由于周期性的地幔活动发生两次向南跃迁,在洋壳内部形成两组对称 LCR 结构的新观点(图 4 右)(Ding *et al.*, 2018).第一次跃迁发生在晚渐新世,即洋盆刚开始扩张不久,扩张脊向南跃迁约 20 km,在洋盆北翼形成了第一个对倾 LCR;第二次发生在 23.8 Ma 左右,即西南次海盆开始扩张时期,形成了第二个对倾 LCR.扩张过程中洋中脊的多次跃迁导致了南海海盆北翼更宽,南翼更窄的不对称结构.

通过对 IODP 349 航次钻井获取的岩心微观结构观测和宏观地球物理的综合分析,笔者发现海盆的不连续扩张过程不仅有扩张脊的多次跃迁,同时也伴随着扩张方向的多次变化(Sun *et al.*, 2019),不仅导致扩张脊北翼比南翼更宽,而且(1)北翼形成更多后扩张期的海山,而这些海山的分布与由原残留洋中脊形成和扩张方向改变形成的岩石圈薄弱带一致(图 5,Zhao *et al.*, 2020);(2)北翼具有更为强烈的热液循环体系(Ding *et al.*, 2017).这是首次从洋壳深部结构的角度发现了扩张脊的多次跳跃、扩张方向多次变化的现象,对南海洋壳在不连续-非对称扩张过程中的增生机制,以及扩张结束后残留扩张脊南北翼构造-岩浆活动的巨大差异的机制进行了较好的理论解释.

3　结论与展望

揭秘南海的生命史有两个最为关键的科学问题,包括(1)南海的扩张历史及过程;(2)南海拉张开始和停止的机制.笔者通过深部结构地震探测,聚焦南海地壳深部结构和三维全变形机制,(1)建立了南海"大陆破裂非均一"的陆缘破裂模式.该破裂模式表现为三维不均一的构造-岩浆过程,包括拉张过程垂向上拉张因子随深部变化的分层不均一,以及最终破裂过程横向上东、西侧陆缘岩浆活动的不均一;(2)构建了南海"海盆扩张非对称"的海盆扩张模式.该扩张模式不仅表现为周期性地幔活动控制下,多幕次洋中脊南向跃迁主导的非对称扩张,而且扩张方向也发生多次变化,不连续-非对称的扩张方式最终导致南海残留洋中脊两翼构造与岩浆活动的不对称性.以上工作对南海拉张-破裂-扩张的过程进行了有益的探索.而对南海海底扩张时间,2014 年的 IODP 349 航次及 2017 年的 IODP 367&368 航次已提供了定论(Li *et al.*, 2015; Sun *et al.*, 2018).这两次钻探分

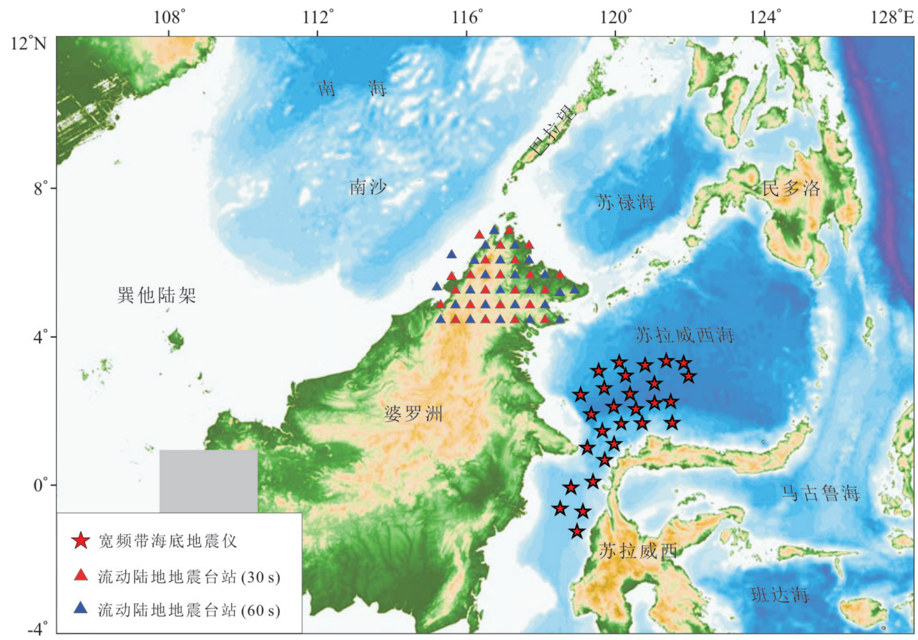

图 5　南海南部苏拉威西海海底地震仪(OBS)(红五角星)及婆罗洲东北部陆地地震台站(红、蓝三角)布设图

Fig.5　Distribution of OBS array deployed in the Celebes Sea (red star), and land seismic stations in northeastern part of Borneo (red & blue triangle)

别在代表最年轻海盆的残留洋中脊区和代表最老海盆的洋陆过渡带区获取了基底玄武岩，对玄武岩同位素定年和玄武岩之上最老沉积物的古生物定年工作，表明南海海底扩张发生在 33～16 Ma之间，验证了 Briais *et al.*(1993)的观点.

但是对于南海初始拉张的动力学机制，却一直存在着诸多的观点，最为经典的包括 Tapponnier *et al.*(1986)提出的碰撞挤出模式，Hall(2002)提出的古南海拖曳模式，徐义刚等(2012)提出的地幔柱模式，Sun *et al.*(2018)提出的特提斯洋闭合过程中形成的弧后扩张模式，以及 Wang *et al.*(2019)提出的岩石圈汇聚背景下的板缘张裂模式.

碰撞挤出模型最大的问题是无法与南海的扩张方式相匹配，即若南海为一个走滑拉分盆地，那么拉张应首先发生在靠近走滑断裂处，也即西侧的哀牢山－红河断裂处，并向东发育，而这与南海由北东向南西的渐进式扩张完全无法匹配(Ding *et al.*, 2016c). 地幔柱模式正处在理论完善过程中，目前对海南地幔柱何时形成尚有疑问(徐义刚等，2012)，海南地幔柱下地幔成像也不清晰，不能确定其起源深度(Xia *et al.*, 2016). 最新研究表明南海北部陆缘古新世－始新世的 OIB 型玄武岩地球化学特征并未发现与海南地幔柱的关联性(Yu *et al.*, 2018).

古南海俯冲有前人在婆罗州和巴拉望找到的大量地质证据支持(如 Morley *et al.*, 2016)，但其最大的挑战是除却浅层的地质证据，没有确切的地球物理证据表明是否在南沙海槽和婆罗州之下存在所谓俯冲的古南海洋壳. 而且古南海的消亡对南海形成起了什么作用？是俯冲拖曳拉开了南海(如 Hall, 2002; Morley, 2002)？还是新特提斯洋俯冲过程中的被动闭合(Sun, 2016；孙卫东等，2018)？

南海受到周缘大型块体的控制，要了解南海拉张的驱动机制，必须开拓视野，跳出南海来看南海. 南海陆缘张裂－扩张驱动机制的关键科学问题是深部的动力学过程，南海的拉张是南部陆缘(包括南沙地块、礼乐滩、巴拉望等)南移，而北侧相对不动，南部是拉动现代南海的火车头. 而且目前南海的海上探测北重南轻，存在大量的探测空白区，因此对南海南部包括婆罗洲，西北侧相接的南沙地区和东南侧相接的苏拉威西海区域深部岩石圈结构及其浅部构造变形响应的研究，将成为认识南海拉张起始和结束机制的关键.

在该区域的工作必须立足国际合作. 2018年中国科学院地质与地球物理研究所、自然资源部第二海洋研究所、英国剑桥大学与印度尼西亚万隆科技学院签署国际合作协议，在上述研究区开展海陆联合天然地震观测计划. 英国剑桥大学已于2018年在

婆罗洲东北部布设50台陆地地震台站,天然地震记录和观测已进行近两年.中国科学院地质地球物理所、自然资源部第二海洋研究所与印尼万隆科技学院共同合作,已在2019年8月在苏拉威西海投放了27台长周期宽频带海底地震仪,并于2020年8月回收(图5).南沙区域的海底观测正在计划中.这一系列在海域与陆地开展的三维联合天然地震深部观测,将首次照亮研究区从海域至陆地的深部岩石圈结构,有效揭示俯冲板片的空间形态、停滞深度等信息,建立起从古南海俯冲－现代南海拉张－南沙地块碰撞－现代南海停止的系统动态演化历程,真实再现南海的"出生－死亡"演化历史.由此增加对南海的整体认识和边缘海系统的理解,从而丰富板块构造理论的动力学机制.

致敬:本文献给广州海洋地质调查局原总工程师姚伯初教授!

我从1999年开始南海大陆边缘动力学的研究,所读的第一本书便是姚总编著的《中美合作调研南海地质专报》.该书是对1985年首次在南海开展的中美联合双船地震探测航次相关成果的系统总结,姚总是中方的首席科学家,D.E.Hayes是美方的首席科学家.该书和姚总发表的一系列文献为我今后的研究奠定了坚实的基础.其后因为共同参加南海的973项目,结识了姚总,他学养深厚,平易近人,给予如我一样的青年学者很大的帮助.姚总是一位杰出的海洋地质学家,是南海深部地震研究的开拓者,为中国海洋事业的发展做出了十分重要的贡献.他的风范将长存于世,激励后人!

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