https://doi.org/10.3799/dqkx.2020.371

被动大陆边缘张-破裂过程与岩浆活动:南海的归属

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摘 要: 岩浆在被动大陆边缘的张-破裂过程中起到决定性作用.南海东北部陆缘发育厚度达10 km的下地壳高速体,其成因机制长期存在争议,影响了对南海东北部陆缘构造归属的界定.为了分析南海共轭陆缘的张破裂机制,本文调研了国内外最新研究进展,系统分析了南海南北陆缘的地壳结构和岩浆活动特点,提出:南海陆缘和海盆中发育有大量岩浆活动,但东西陆缘存在较大差异,底侵高速体东厚西薄,推测为同张裂成因.根据地壳结构与底侵岩浆的量,将被动陆缘划分为5个子类,南海陆缘东侧为多岩浆型,向西变为少岩浆型.东西差异除与伸展速率有关,可能还与东侧陆缘发生了板缘破裂,而西侧陆缘发生了板内破裂有关.

关键词: 被动大陆边缘;张裂与破裂;岩浆作用;南海;板内与板缘破裂;海洋地质.

中图分类号: P736 **文章编号:** 1000-2383(2021)03-770-20 **收稿日期:** 2020-11-15

The Rifting-Breakup Process of the Passive Continental Margin and Its Relationship with Magmatism: The Attribution of the South China Sea

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Abstract: Magma plays a key role in the rifting and breakup process of passive continental margin. Up to 10 km thick high velocity lower crust (HVLC) developed in the northeastern margin. Long term controversy toward its formation mechanism makes the margin classification difficult. In order to analyze the rifting and breakup mechanism of the SCS conjugate margins, this paper reviews the recent research progress of global margins, based on which the crustal structure and magmatic activity of the SCS are

基金项目: 广东省自然科学基金研究团队项目(No.2017A030312002);南方海洋科学与工程广东省实验室(广州)人才团队引进重大专项(Nos. GML2019ZD0104,2019BT02H594,GML2019ZD0205);王宽诚教育基金项目(No.GJTD-2018-13).

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引用格式: 孙珍,李付成,林间,等,2021.被动大陆边缘张-破裂过程与岩浆活动:南海的归属.地球科学,46(3):770-789.

summarized. It is concluded that large amounts of magmatic activity occurred in the SCS with discrepancy between the eastern and western margins. The HVLC is thicker in the east and thinner or even absent in the west. It is speculated that the HVLC is of syn-rift underplating. According to the crustal structure and the amount of underplated magma, we suggest that the passive continental margin can be divided into 5 subclasses. The eastern continental margin of the SCS is of magma-robust type, and the middle and western margins are of magma-intermediate and magma-deficient types, respectively. In addition to the stretching rate, plate-edge rifting in the east and plate-interior rifting in the west continental margin may also contribute to the large difference in the amount of magmatic underplating.

Key words: passive continental margin; rifting-breakup process; magmatism; South China Sea; plate interior and plate edge breakup; marine geology.

1 被动陆缘张—破裂过程与岩浆活动的关系

被动大陆边缘因蕴含丰富的油气—水合物资源(Sun *et al.*, 2009; 朱伟林等, 2012; 任建业等, 2015),保存有构造—沉积和气候环境演变的重要信息(汪品先和翦知湣, 2019),而成为国际上长期研究的热点.陆缘张—破裂过程,是大陆解体和新洋盆诞生的一个重要方式,是板块构造演化的重要环节.因此,在过去的30多年里,科学家们综合运用重、磁、震、电等多种地球物理探测方法,通过10多个大洋钻探航次、岩石地球化学以及物理数值模拟实验等多种方式,对被动陆缘的张—破裂过程进行了深入的探索,在陆缘结构、演化、发育机制和分类等方面取得了一系列进展(孙珍等, 2016, 2020).科学家们发现,岩浆在被动大陆边缘的张裂和破裂过程中起到决定性作用;即使极度缺乏岩浆的伊伯利亚大陆边缘,张裂早期的野外露头中也发育有侵位到地表的岩浆作用(Peace *et al.*, 2018),从陆向洋的转换也是在解压熔融产生岩浆达到足够的量之后实现的(Bronner *et al.*, 2011).因此,以大西洋为蓝本,科学家们将被动大陆边缘划分为两个端元(图1, Franke, 2013):富岩浆型(或称火山型)和贫岩浆型(或称非火山型).区分两个端元类型的标准是:大陆岩石圈破裂前后,是否存在大量的岩浆侵入(包括底侵高速层与侵入岩墙)和喷发(地震上具有向海倾斜反射特征的苦橄玄武岩和少量中性流纹岩与少量陆缘沉积岩互层的沉积层序)(Huismansand Beaumont, 2014; Geoffroy *et al.*, 2015; Clerc *et al.*, 2018).下面将结合国内外最新研究进展,总结一下端元类型的特点及其与岩浆作用的关系.

1.1 被动陆缘端元类型的结构特点

富岩浆型大陆边缘被认为常与地幔柱/热点有关,后者提供的富镁岩浆,导致下地壳底部存在底侵辉长岩和堆晶体层,从而具有高速特征(White and McKenzie, 1989; Clerc *et al.*, 2018).富岩浆型陆缘研究较多集中在英格兰—格陵兰陆缘(Roberts *et al.*, 1984; Eldholm *et al.*, 1987, 1989; Larsen, 1994, 1998; Duncan *et al.*, 1996; Gernigon *et al.*, 2004; Eccles *et al.*, 2011).贫岩浆型陆缘没有热点参与,岩浆主要在解压熔融作用下产生.在贫岩浆型陆缘中,伊伯利亚—纽芬兰陆缘被研究得最多,那里洋陆过渡带上存在宽度达上百公里的地幔剥露,造成橄榄岩发生蛇纹石化(Boillot *et al.*, 1980, 1995; Manatschal *et al.*, 1999; Reston, 2009; Whitmarsh *et al.*, 2001).地球物理探测表明(Bayrakci *et al.*, 2016),蛇纹石化主要发生在同张裂阶段,活动的断裂将水带入地幔,导致橄榄岩发生蛇纹石化.数值模拟研究表明,慢速—超慢速的拉张速率、地幔亏损或地幔温度低等原因,可以导致岩浆生成过程变慢、岩浆量少,因而地壳发生破裂,地幔经历拉张暴露(Pérez-Gussinyé *et al.*, 2006).前人对伊伯利亚型陆缘的认识,目前已被拓展到全球的大部分陆缘(Tugend *et al.*, 2018; Gillard *et al.*, 2019).

对更多陆缘的观测表明,富岩浆型陆缘的定义比较窄,而贫岩浆型陆缘的定义却很宽泛,所有未同时发育底侵高速层和地表喷发岩浆序列的陆缘都被划入贫岩浆型大陆边缘(Clerc *et al.*, 2018).因此贫岩浆型陆缘既包含了像伊伯利亚这样极度贫岩浆的类型,也包含了岩浆量比较多的类型,如南大西洋陆缘和南海东部陆缘(Becker *et al.*, 2014; Sun *et al.*, 2019).此外,通过对南大西洋热点附近到远离热点的陆缘地壳结构的探测研究,Becker *et al.* (2014)发现距离热点较近的陆缘表现为典型的富岩浆型(底侵+喷发)特征,而距离热点较远的区域,仅发育有下地壳高速体(底侵)、缺少向海倾斜反射喷发层序,为贫岩浆型陆缘.因此,简单地将陆缘划分为富岩浆型或贫岩浆型两个极端端元,会导

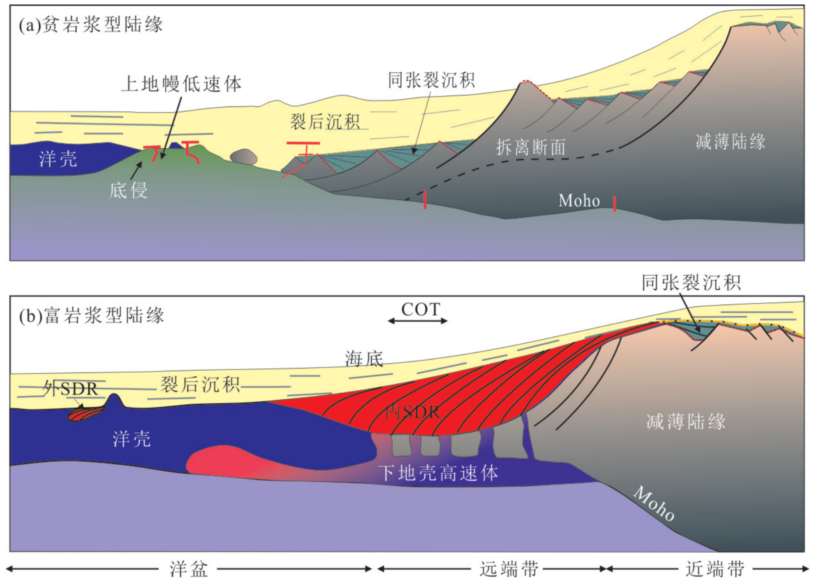

图1　贫岩浆型和富岩浆型被动大陆边缘结构特征示意剖面

Fig.1　The diagram showing the main profile features of magma-poor and magma-rich margins

据Franke(2013)修改

致人们对贫岩浆型陆缘结构特征总结的困难和偏差.需要建立更合适的标准,进行更加合理的分类.

1.2　被动陆缘岩浆作用与张破裂关系

科学家们很早就关注到,拉张应力可以导致岩石圈变薄和破裂,这一薄化破裂过程将对软流圈造成解压熔融,进而导致岩浆形成并发生侵位和喷发(McKenzie, 1978; Royden and Keen, 1980; Braun and Beaumont, 1989; Buck, 1991; Davis and Kusznir, 2004).越来越多的野外露头(Fialko and Rubin, 1999; Peace *et al.*, 2018)和钻探研究(Bronner *et al.*, 2011)表明,陆缘(包括富岩浆型和贫岩浆型)的岩浆作用早在岩石圈减薄之前就发生了,岩脉宽度可达几十到几百米,且岩脉的侵位方式与断裂等伸展构造没有必然的关系.数值模拟表明,产生一条几十到几百米宽的岩脉所需的伸展应力,要远远小于产生一条拉张断层所需的应力(Buck, 2004),且岩石圈厚度越大,产生断裂所需的伸展应力就越大,因而岩石圈越难断裂.因此,Buck(2006)、Qin and Buck(2008)以及Bialas *et al.*(2010)提出,岩石圈伸展的早期,拉张应力首先会导致岩脉沿着岩石圈内的裂缝上涌,高温岩脉的加入会导致岩石圈流变结构弱化,从而有利于岩石圈在相同的张应力下发生更大的变形.但岩浆作用是否导致岩石圈弱化与岩浆侵入的体量和速率有很大关系.

根据拉张过程中变形对岩浆的需要情况,Bialas *et al.*(2010)将变形过程分为需要脉体的岩浆阶段和不需要岩浆加入也可以变形的构造阶段.但实际上,即使进入构造阶段,岩浆作用还是会在伸展应力和解压作用下不断产生,因此多数陆缘岩石圈的伸展破裂是个加速过程(Brune *et al.*, 2016).脆性上地壳和上地幔由于温度和岩石组成等原因,常发生脆性断裂,下地壳则会由于温度压力等原因表现出或脆性或韧性的不同流变学行为.因此,岩石圈不同圈层破裂的时间常不同,会发生与深度相关的破裂(Davis and Kusznir, 2004).由于流变性质的差异,伸展过程中地壳与地幔、甚至脆性上地壳和上地幔与韧性下地壳之间常常发生解耦.解耦作用常在不同流变结构的圈层之间产生空间,有利于岩浆沿水平方向的侵位,发生底侵.

实验表明,地幔熔融物质在莫霍压力下的密度超过了大陆地壳的平均密度,因此在单纯的重力平衡的情况下,岩浆不会上升到或接近地面;但在地壳熔化和脱气开始以后,岩浆才更易上升(Fyfe, 1992; Bialas *et al.*, 2010).由于岩浆密度与地壳密度接近,岩浆最容易在壳幔之间发生底侵,形成地震上的高速下地壳,岩浆上升到地壳及沉积层中后,也更倾向于沿水平方向侵位.地震观测表明,构造静止期的热点型地壳结构常表现为狭窄的火山状速度异常(Yang and Shen, 2005; Jokat and Hagen, 2017; Ryberg *et al.*, 2017),与同伸展期的岩浆底侵特征截然不同.

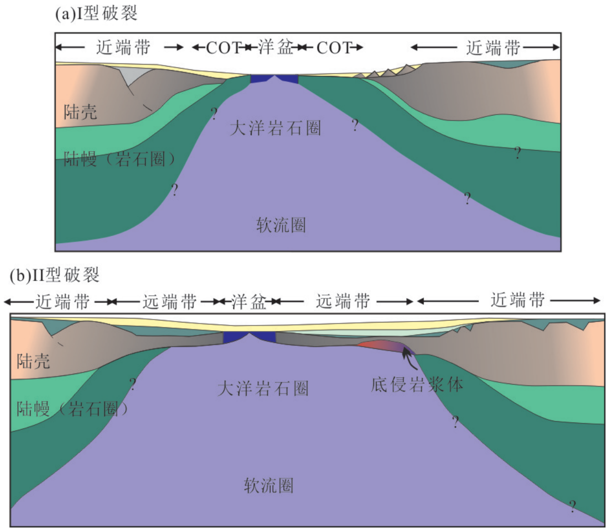

图2　I型(a)和II型(b)破裂剖面模式

Fig.2　Diagram of type I (a) and type II (b) breakup in magma-poor margin

Huismans and Beaumont(2011, 2014).I型破裂特点:断裂切割深度大,地壳断裂区域窄,隆凹结构不对称,地壳早于地幔破裂,洋陆过渡带上有地幔剥露和蛇纹石化,拉张过程中岩浆量有限,洋盆发育和正常地壳厚度出现较晚;II型破裂特点:地壳强烈减薄区域宽,同张裂早期盆地沉积发育断裂,同张裂晚期沉积不变形,晚期沉积发育在浅水凹陷中,同张裂沉降亏损,无地幔剥露但有同张裂岩浆活动,存在岩浆底侵速度异常体,地壳破裂后很快发育正常洋壳

通过数值模拟,Huismans and Beaumont (2011, 2014)提出,贫岩浆型陆缘的破裂方式主要分为两种(图2):I型破裂中地壳破裂早于地幔;II型破裂中地幔破裂早于地壳.I型破裂主要发生在慢速-超慢速伸展陆缘,由于陆洋转换速度缓慢,下地壳常由于上地壳变薄而变冷、脆化,发生断裂,导致地幔与海水接触发生蛇纹石化,因此陆洋转换常以过渡带的方式完成(Pérez-Gussinyé and Reston,2001;Huismans and Beaumont, 2011, 2014).Ros　*et al.*(2017)认为,当下地壳比较硬的时候,易形成I型破裂;当下地壳比较软时,则无论什么拉张速率,陆缘都会以II型方式破裂.发生II型破裂的一个重要原因是韧性的下地壳起到解耦作用,脆性的上地壳和上地幔在断裂和地幔对流的作用下易早于韧性地壳发生破裂.由于陆洋转换完成速度较快,陆洋转换带应该是截然变化的断裂式或狭窄的岩浆型过渡带,后者一般表现为底侵岩浆与喷发岩浆夹减薄地壳的三明治方式(Tugend *et al.*,2018).富岩浆型陆缘由于软流圈对流作用强,常发生地幔早于地壳破裂的情况(Geoffroy *et al.*,2015).相对于I型陆缘,II型陆缘宽度大、常发生岩浆底侵、断裂断距小且同张裂后期缺少或缺失断裂、张裂期水深小、地表热流高等,二者各方面表现都明显不同(Huismans and Beaumont,2011, 2014).

2　南海陆缘地壳结构、岩浆活动特点与机制

南海是我国最大的边缘海,也是唯一一个发育了洋盆的海.长期的研究揭示,南海是在晚中生代-早新生代经陆缘拉张-破裂-海底扩张等过程发育而成(图3),为拉张成因的被动陆缘(Sun *et al.*,2009).其在全球被动陆缘框架里代表了一个发育较为完善的边缘海,其早期形式与加利福尼亚湾和红海等有一定相似性.为了揭示南海的陆缘结构及其演化机制,科学家们开展了大量深部结构探测工作.

2.1　南海陆缘地壳结构(图4)

姚伯初等(1994a,1994b)是首批利用双船反射确定了南海北部陆缘地壳一维速度结构的科学家,他们发现并提出南海北部陆缘地壳呈阶梯式减薄的结构特点,并首次揭示高速下地壳的存在,发现东侧陆缘高速下地壳厚度大,速度高(P波速度7.1~7.4 km/s),西侧厚度小,速度偏低(<7.1 km/s).美方合作者进一步给出了沿剖面的地壳速度结构变化,进一步证实了下地壳高速体东厚西薄的特征(Nissen *et al.*,1995).这些发现奠定了南海陆缘地壳结构认识的基础,为南海陆缘演化分析提供了重要的约束.之后,科学家们运用OBS观测地壳结构,发现了类似的规律(Qiu *et al.*,2001; Yan *et al.*,2001;Wang *et al.*,2006; Ding *et al.*,2012; Lester *et al.*,2014; Pichot *et al.*,2014; Huang *et al.*,2019).不同学者对上/下地壳分界和高速体顶界速度界定有差异,上下地壳分界速度一般选6.4 km/s或6.5 km/s,高速体顶界选择从6.8~7.1 km/s不等,为了更好地对比地壳结构,在原作者给出了等值线数值的情况下,笔者尽量以7.0 km/s为上限值,重新圈画了下地壳高速体范围(图4g,4i,4j).部分早期工作未给出速度等值线,无法重新圈画,因此保留了原作者划分方案(图4d).另外,在空间位置接近的区域,也存在不同学者得到的地壳结构不一致,如剖面i(Huang *et al.*,2019)和剖面k(Pichot *et al.*,2014).因此这里对高速体分布的认识应该有一定的误差.

总体的特征是,大致以中南-礼乐断裂为界,

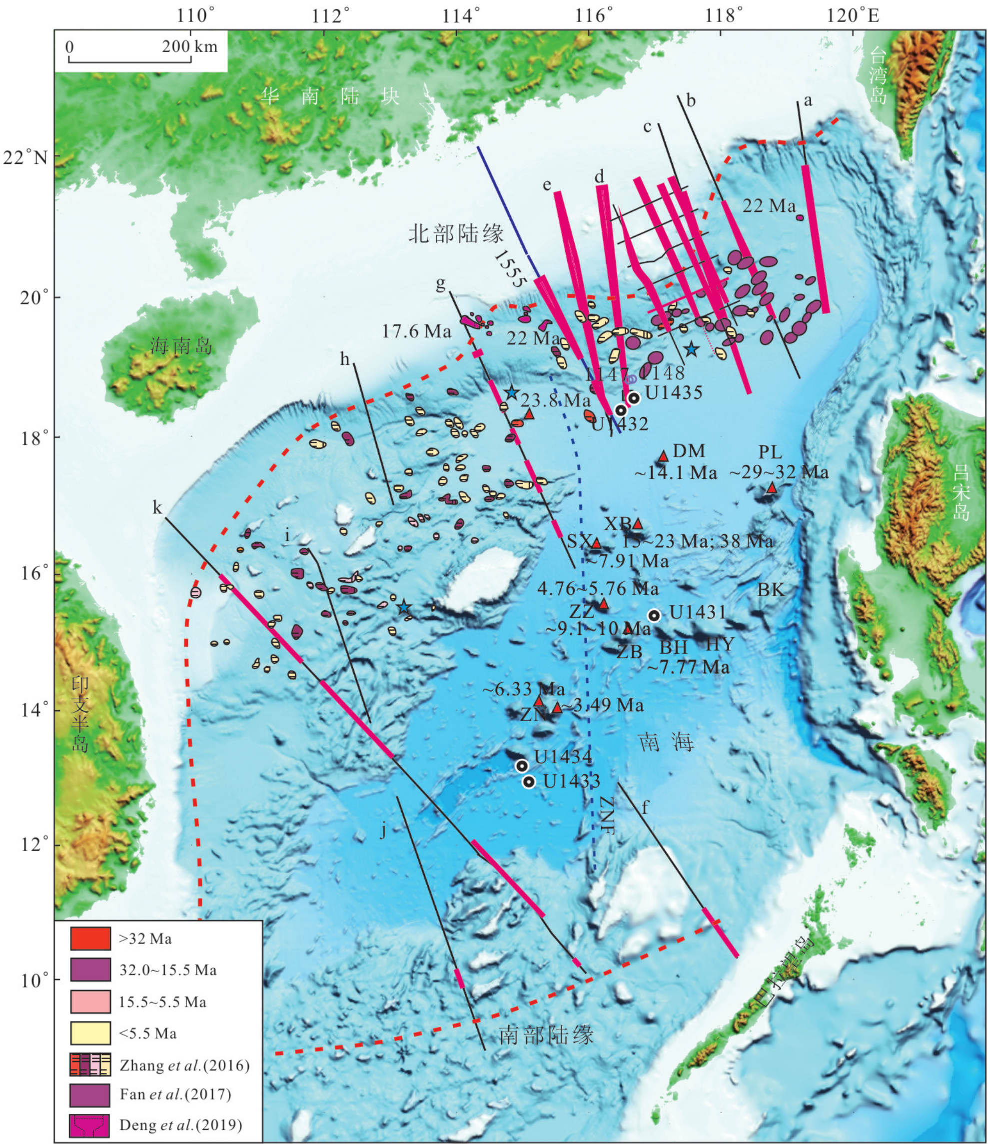

图 3　南海陆缘与海盆中岩浆活动与下地壳高速体分布

Fig.3　The distribution of magmatic activity and high velocity lower crust in the South China Sea

岩浆分布及其活动时间据 Zhang *et al.*（2016）、Fan *et al.*（2017，2019）和 Deng *et al.*（2019）；侵入岩席和（或）岩墙等出现的范围大致在红色虚线至洋盆区域（Song *et al.*，2017），但南部陆缘由于地震剖面覆盖限制，其范围不准确．黑色实线为 OBS（ocean bottom seismometer）测线（剖面图见图 4），红色粗实线是剖面上揭示了下地壳高速体的范围；深蓝色实线为多道地震剖面（见图 5）

南海陆缘东西侧地壳结构在上/下地壳厚度比和变形特点等方面都具有明显的不同（图 3）．东侧陆缘下地壳较厚，上下地壳厚度比较小，陆架区上下地壳厚度比为 1.2 或更小（Yan *et al.*，2001；Wang *et al.*，2006；卫小冬等，2011；曹敬贺等，2014），陆坡区下地壳厚度减薄较快，但底侵高速体下地壳厚度较大，最大可达 10～12 km，从而导致陆坡区下地壳总厚度较大；控盆断裂由犁式断裂和低角度拆离断裂构成（Lei *et al.*，2019；Zhang *et al.*，2019）．南北陆缘的宽度不对称，如珠江口盆地陆缘宽度超过 450 km，但礼乐及其以东区域陆缘宽度仅约 200～300 km（孙珍等，2006，2011；Franke *et al.*，2014；Bai *et al.*，2015）；西侧陆缘下地壳较薄，上下地壳厚度比可达 1.5～2.0（张远泽等，2019；毛云华等，2020）；下地壳高速体厚度薄或缺失，高速层分布不连续（Qiu *et al.*，2001；Ding *et al.*，2012；Pichot *et al.*，2014；Huang *et al.*，2019），局部区域发现上地幔低速体，但范围有限（Savva *et al.*，2014）．多数控盆断裂仍为犁式断裂（Lei *et al.*，2020），南北宽度相对接近．

2.2　南海陆缘的岩浆活动特点（图 3）

南海是岩浆活动非常活跃的区域，根据钻井、

拖网和地球物理成像分析结果，南海新生代的岩浆活动表现为：多种样式、多期、多成分等特征．钻井/拖网采样、多道地震和OBS观测分析表明（Zhao *et al.*，2010；Yan *et al.*，2014；Song *et al.*，2017），南海陆缘和海盆中的岩浆活动至少包括3种形式：底侵（近水平）、侵入（近垂直）、火山喷发（岩浆到达地表）．三类岩浆侵位在空间上常相互关联（Fan *et al.*，2017；Xia *et al.*，2018；Sun *et al.*，2019a）．

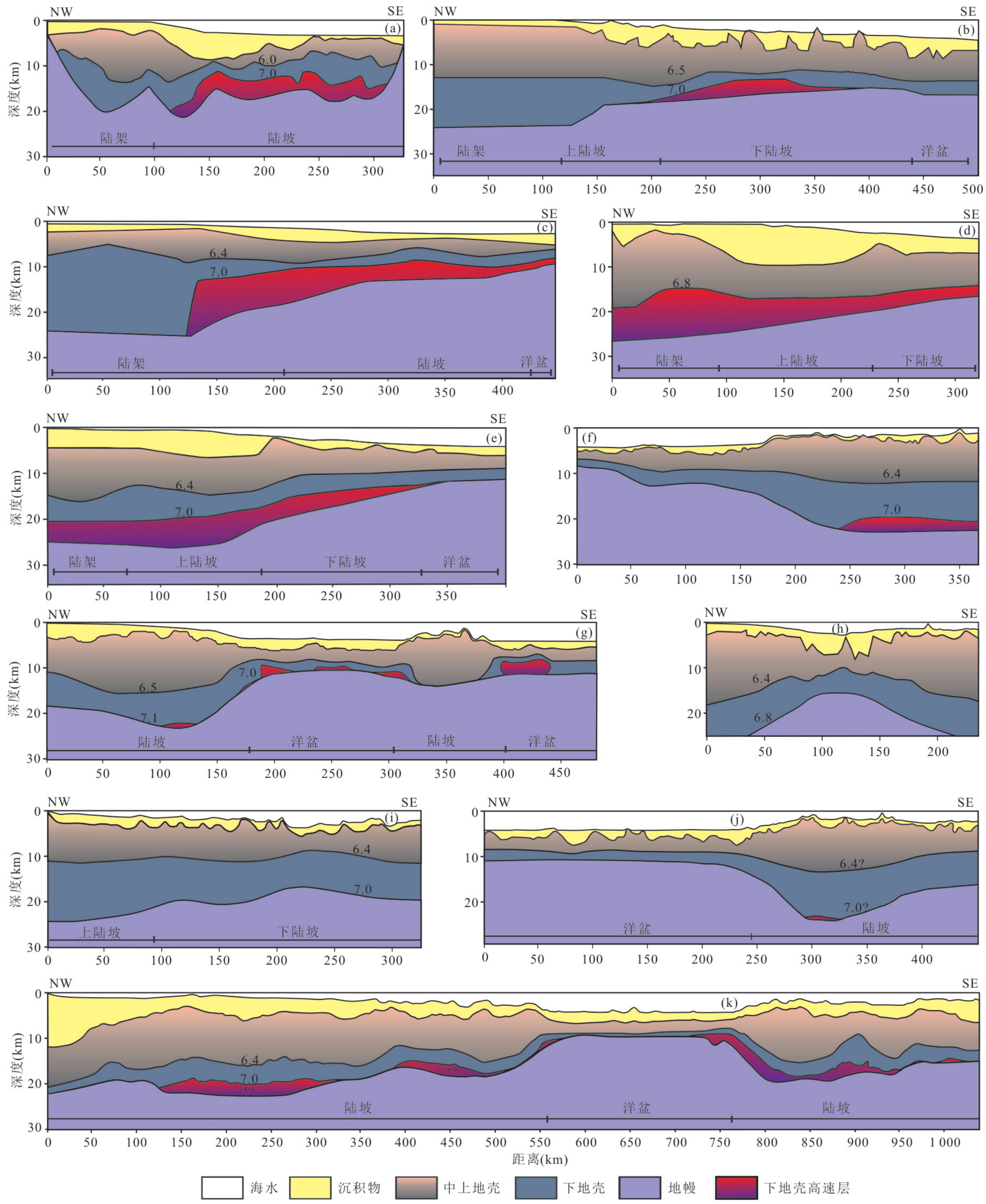

图4　南海陆缘地壳结构与下地壳高速体分布剖面

Fig.4　The crustal structure and the distribution of high velocity lower crust in the profile

图中数据单位：km/s. a. 剖面OBST3，据Lester *et al.*（2014）；b. 剖面OBS2001，据Wang *et al.*（2006）；c. 剖面ESP-E，据Nissen *et al.*（1995）；d. 剖面OBS2006-3，据卫小冬等（2011）；e. 剖面OBS1993，据Yan *et al.*（2001）；f. 剖面OBS973-2，据阮爱国等（2011）；g. 剖面OBS2006-1，据Ding *et al.*（2012）；h. 剖面OBH-IV，据Qiu *et al.*（2001）；i. 剖面OBS2011-1，据Huang *et al.*（2019）；j. 剖面OBS973-1，据丘学林等（2011）；k. 剖面，据Pichot *et al.*（2014）

2.2.1　底侵岩浆岩体空间分布　底侵作用主要通过OBS高速层及与Moho面平行的反射层(Sun *et al.*, 2019a)来辨别.下地壳与上地幔之间常检测到下地壳高速体或上地幔低速层,其纵波速度大于7.0 km/s(通常速度范围为7.1~7.7 km/s).产生这一速度异常体的原因主要有3种(Gernigon *et al.*, 2004;孙珍等,2016):(1)基性－超基性的辉长岩和橄榄岩堆积体;(2)上地幔蛇纹石化;(3)变质基底,如榴辉岩等.一般岩浆底侵和变质成因,称之为下地壳高速体;蛇纹石化成因,称之为上地幔低速层.区分的主要方法是:变质基底的密度和地震速度都较大,具有明显重力异常但不具备磁力异常(Fountain *et al.*, 1994);上地幔蛇纹石化区域地壳厚度一般较薄(通常认为<5 km),且Moho反射不清甚至没有,速度波动可能较大,如5.0~7.5 km/s,纵横波速度比大于1.8;底侵岩浆体的速度变化相对较小,通常为7.1~7.7 km/s,纵横波速度比较小,一般为1.75~1.85.地震速度结构和纵横波速度比结果显示,南海陆缘下地壳高速体主要见于北部陆缘,南部陆缘仅零星发现下地壳高速体或上地幔低速层(图3和图4).南海北部陆缘的多数高速层为岩浆底侵成因(Zhao *et al.*, 2010; Wan *et al.*, 2017),局部可能存在地幔蛇纹石化成因(Savva *et al.*, 2014; Hou *et al.*, 2019).

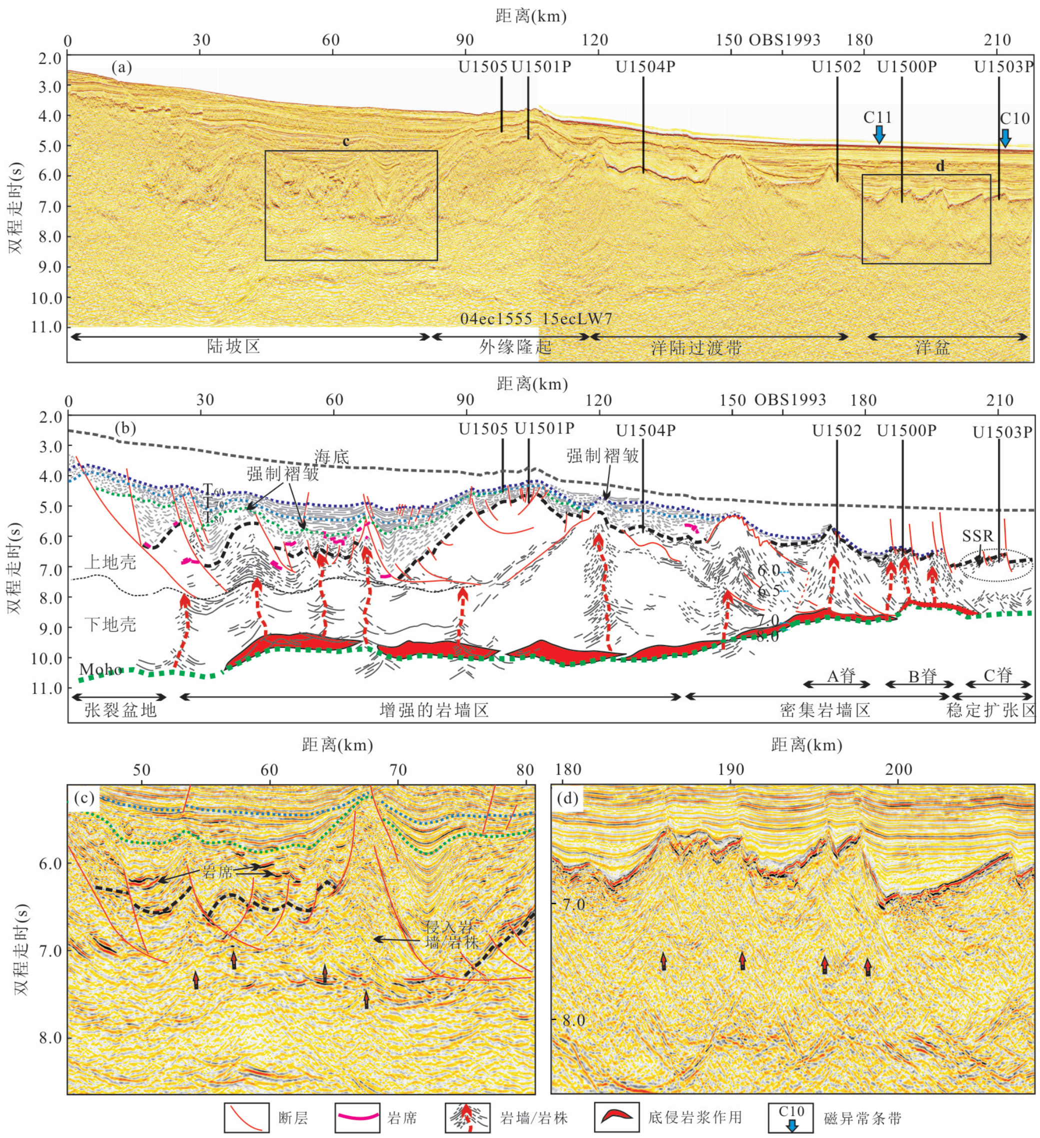

图5　反射地震剖面上观察到的岩浆底侵、侵入岩墙和岩席特征

Fig.5　Magmatic underplating, intruding dikes and sills observed on multi-channel reflection seismic profile

据Sun *et al.*(2019a)修改.a.原始剖面;b.构造解释线描图;c,d.局部放大图,图件c和d在剖面中的位置见图a中的矩形框

2.2.2　侵入岩浆岩体的空间分布　垂向侵入的岩浆体较难以准确成像，特别是当侵入体宽度较窄时．科学家们主要通过多道地震剖面上的反射异常（如较常见的"人"字形上拉反射）和两侧顺层侵位形成的岩席等特征来识别（Reynolds *et al.*, 2017）；根据上覆地层变形（如强制褶皱）、地层厚度变化和局部地层抬升削截等构造现象判断岩浆侵入发生的时间（Schmiedel *et al.*, 2017；Wang *et al.*, 2019a）．依据上述特征开展多道地震解释，结果表明南海陆缘的岩浆侵入多发生在强烈减薄的陆坡－洋陆过渡带区域（图3和图5）（Song *et al.*, 2017；Fan *et al.*, 2017；Xia *et al.*, 2018；Sun *et al.*, 2019a），且主要出现在珠江口盆地和西北次海盆以北等区域（Zhang *et al.*, 2016）．

2.2.3　喷发岩浆岩体的空间分布　喷发型岩浆体分布范围较广，但多数体积比较小，年龄比较轻，东部陆缘同扩张期岩浆喷发多于西部陆缘，南海北部陆缘洋陆过渡带附近显示有较多23 Ma以来的岩浆作用（Xie *et al.*, 2017；Fan *et al.*, 2017）；西侧陆缘扩张后岩浆喷发作用比东部陆缘多（Zhang *et al.*, 2016；Song *et al.*, 2017；Wang *et al.*, 2019a, 2020）．洋盆里的岩浆作用总体上向扩张脊变年轻，扩张脊附近海山主要喷发于10～3 Ma（图3）（任江波等，2013；Sun *et al.*, 2019b）．

2.3　岩浆岩体的活动时间和机制

华南陆上和沿海的采样结果表明，南海自中生代到新生代晚期，一直有岩浆活动（Xu *et al.*, 2012；Huang *et al.*, 2013）．根据年龄统计，南海及周边陆缘在张裂早期和扩张结束之后，火山喷发作用较多，同扩张期岩浆喷发较少（Xu *et al.*, 2012），10 Ma以来的火山活动最多（Xu *et al.*, 2012；Zhang *et al.*, 2016）．地球化学分析表明，多数火山活动表现出富集组分特征，前人推测与深源的地幔岩浆和俯冲板片循环物质有关（Yu *et al.*, 2018；Zhang *et al.*, 2018）．陆上岩浆喷发活动峰期时间与海南地幔柱时间（0.6～13.0 Ma，峰期是～4 Ma；据Wang *et al.*, 2012）接近．因此多数人将南海东北部陆缘的下地壳高速体和岩浆活动也归因于裂后或扩张后地幔柱/热点成因（Zhao *et al.*, 2010；Fan *et al.*, 2017；Xia *et al.*, 2018）．从地球化学证据来看，地幔柱/热点的影响至少发生在25 Ma以后（Yu *et al.*, 2018），这与Yu and Liu（2020）对U1500钻遇玄武岩的地球化学分析结果一致，该站位岩浆活动未发现地幔柱/热点信号．

也有部分学者将下地壳高速体划为裂前（中生代）（Nissen *et al.*, 1995）．但姚伯初（1998）提出，南海陆缘高速层为新生代同张裂基性岩浆底侵成因，陆缘地壳结构存在横向变化，反映了改造陆缘地壳结构的新生代张性构造运动强度的横向变化．刘安等（2008）详细论述了高速层的可能成因，并认为高速层为岩浆底侵，底侵时间为T_{70}前后．Wan *et al.*（2017）认为高速层有两种成因，东沙隆起附近的高速层为中生代火山弧成因，陆坡－洋陆过渡带附近的为同张裂底侵成因．Sun *et al.*（2019）指出高速层的分布与侵入岩浆体和之上的穹窿抬升及强制褶皱变形密切相关，根据穹窿和强制褶皱的变形时间，底侵的时间为T_{80}（～40 Ma）～T_{60}（～24 Ma）前后，且西北早，向东南逐渐变晚．

裂后（含同扩张及扩张后）的岩浆活动，多数分布在地壳减薄强烈的陆缘和海盆区（Zhang *et al.*, 2016；Song *et al.*, 2017；Gao *et al.*, 2019），与岩石圈强烈减薄范围一致（图4）；笔者推测裂后岩浆活动可能一定程度上受到同张裂岩浆作用的继承性影响，其成因可能与陆缘冷却收缩（Song *et al.*, 2017）、新构造运动（如菲律宾海板块沿马尼拉海沟向南海仰冲、红河断裂右行走滑）（Zhang *et al.*, 2016）、海南地幔柱相关的岩浆活动（Xia *et al.*, 2018）等多种因素有关．数值模拟表明，南海周围俯冲带的持续俯冲可造成南海深部地幔的上涌，形成类似地幔热点的作用（Lin *et al.*, 2019）．热收缩或新构造运动产生的裂缝很可能为这些上涌的岩浆提供了喷出通道．数值模拟从动力学上将地表的岩浆活动与板块运动联系在了一起，给出了裂后岩浆活动的一个较合理的解释．

3　南海陆缘张－破裂特征与构造归属

3.1　新的分类建议（5类）

根据对贫岩浆型和富岩浆型陆缘的研究，Tugend *et al.*（2018）等提出了陆洋转换带的三明治结构，即地表喷发的玄武岩与底侵的辉长岩之间夹裹着变薄的陆缘地壳/岩石圈．Bronner *et al.*（2011）综合运用OBS、钻井和重磁反演，提出贫岩浆型陆缘在地表玄武岩稳定喷发前，剥露蛇纹石化地幔下已有一定厚度的岩浆底侵体．而陆缘类型的分类主要

依据同张裂—破裂前后的岩浆量，因此定量的计算同张裂和破裂初期的岩浆量对准确评价陆缘类型和状态具有重要意义．然而，岩浆量的识别和计算是非常困难的技术问题，通常情况下人们根据多道地震剖面内上拉反射异常圈出岩席/岩脉/岩盖/火山体范围，计算出面积或体积（Planke *et al.*，2000，2005；Calvès *et al.*，2011；Reynolds *et al.*，2017；Fan *et al.*，2017；Wang *et al.*，2019a；Zhang *et al.*，2020a）．Tugend *et al.*（2018）提出了印度东部富岩浆型陆缘的岩浆量计算方法．但实际上这个过程是需要OBS数据、反射地震数据和钻井等条件的约束才能较准确地计算出结果．因此，更详细或定量的分类方案未必适合，结合已发表的北大西洋（Davy *et al.*，2016；Franke，2013）、南大西洋（Becker *et al.*，2014）、南海（Zhao *et al.*，2010；卫小冬等，2011；Ding *et al.*，2013，2016；Wan *et al.*，2017）的陆缘结构与岩浆特点情况，笔者建议被动陆缘划分为5个子类（图6），具体对应特征有：

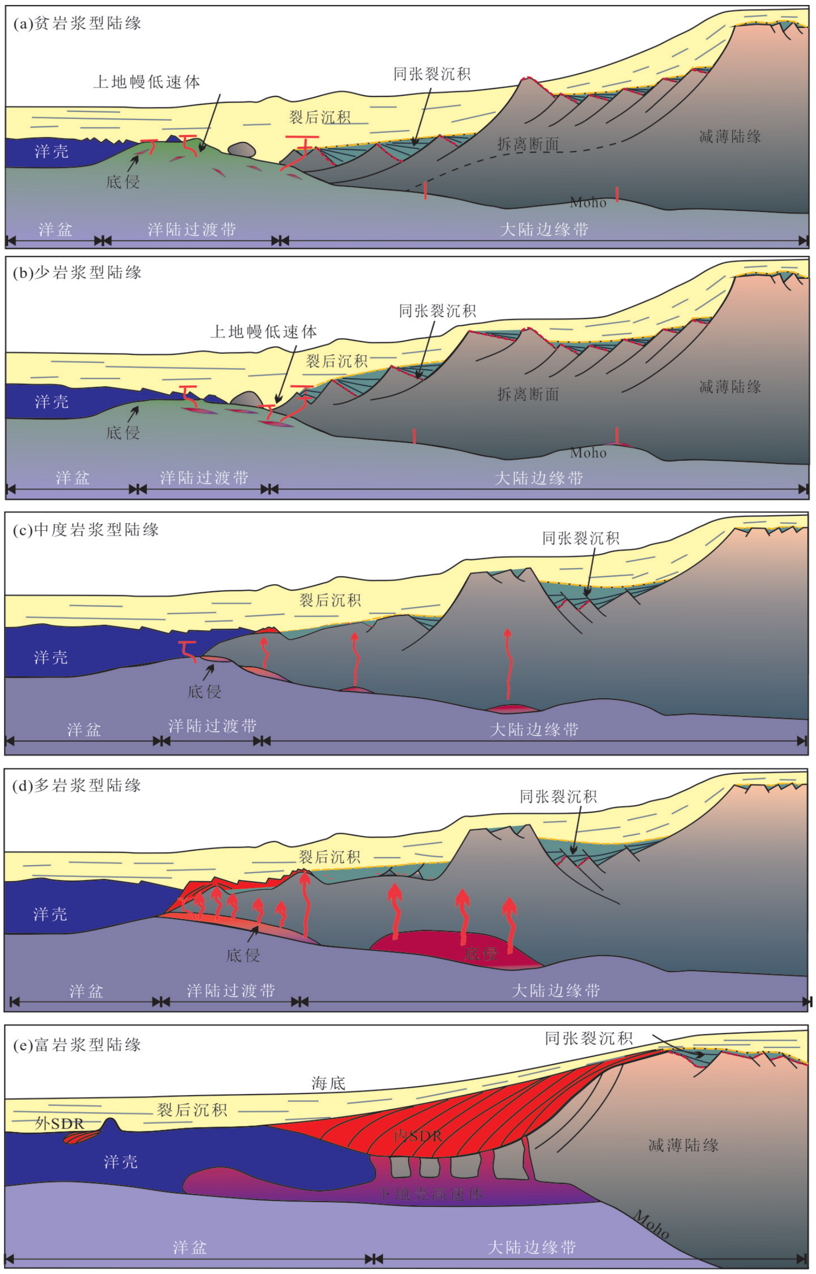

图6　被动大陆边缘根据张-破裂期间的岩浆量进行的陆缘分类模式

Fig.6　The suggested five types of passive continental margin according to the amount of magmatism involved in rifting and breakup

图a、e据Franke（2013）修改；图b～d根据南海陆缘及其他被动陆缘的特征绘制

(1)贫岩浆型(magma-poor):洋陆之间有一定宽度和范围的地幔剥露,典型代表如伊伯利亚－纽芬兰,那里地幔剥露范围可达 100 km 以上.

(2)少岩浆型(magma-deficient):局部有地幔剥露,无岩浆底侵或仅见局部和少量底侵,如南海陆缘西南角,那里仅有少量拆离断层和局部的地幔剥露至海底,未见或仅见到少量岩浆底侵.

(3)中岩浆型(magma-intermediate):无地幔剥露,仅有小范围或较薄岩浆底侵,如南海中西部陆缘.

(4)多岩浆型(magma-robust):有明显厚度(一般>2 km)、分布范围较大的岩浆底侵,无向海倾斜反射喷发层序,如南海东北部陆缘和南大西洋南部陆缘.

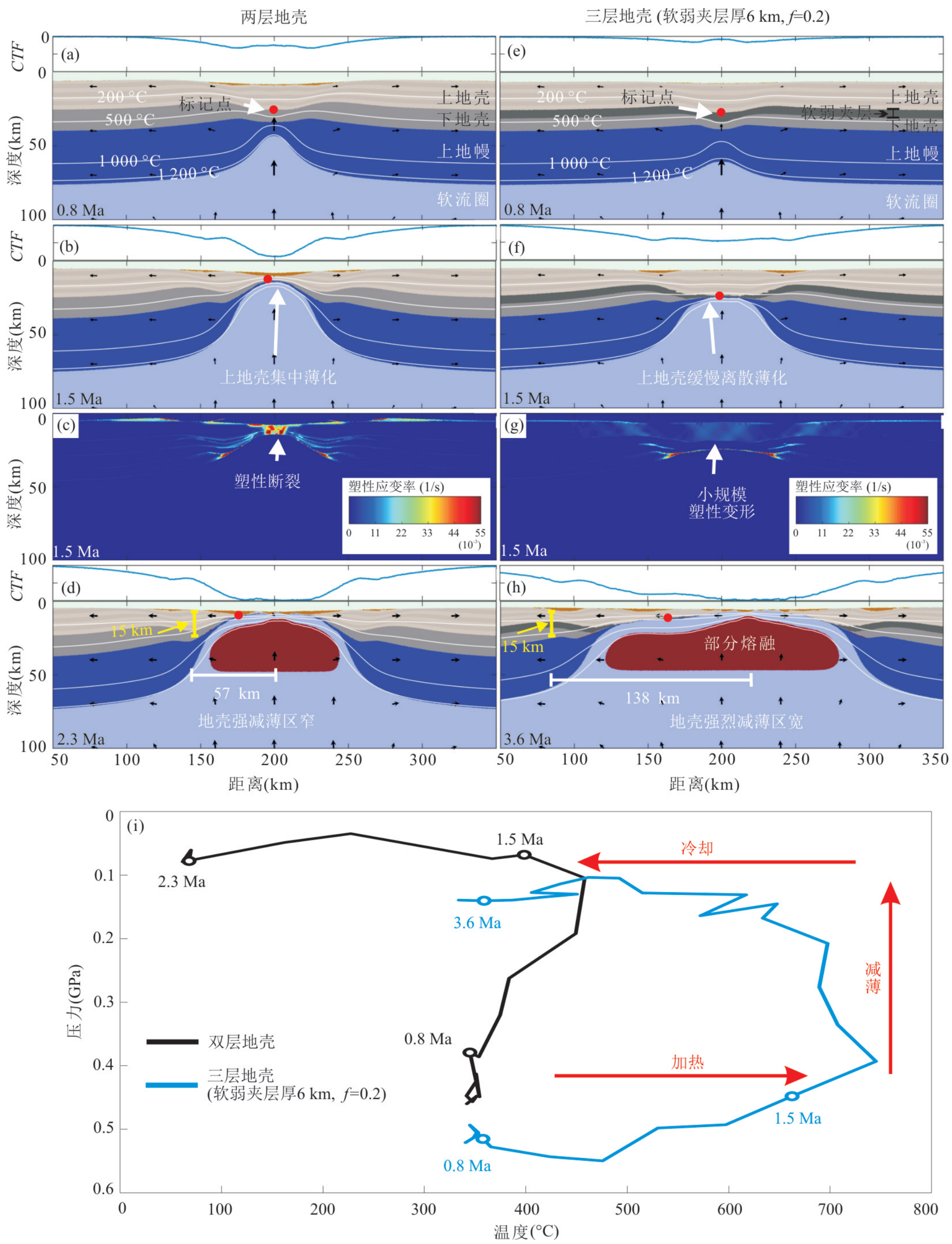

图 7　双层和三层(含软弱中下地壳)地壳发生伸展破裂的结构(a～h)和热状态(i)特征对比

Fig.7　The comparison of rifting structure (a—h) and thermal situation (i) between two-layer and three-layer (with weak middle to lower crust) crust

a～d. 双层地壳;e～h. 三层地壳;*CTF*. 地壳减薄因子;图 i 据 Li *et al*.(2019)修改,其中 *f* 为强度与正常地壳相比的比例因子

(5)富岩浆型(magma-rich):既有岩浆底侵,又有向海倾斜反射喷发层序,如格陵兰－挪威陆缘.

3.2 南海陆缘的构造归属及影响因素

南海由于不发育向海倾斜层序,被划入非火山型大陆边缘(吴世敏等,2001;阎贫和刘海龄,2002;李家彪,2011;郝天珧等,2011;李三忠等,2012;任建业等,2015).地震探测和拖网/钻井结果表明,南海陆缘都为宽陆缘,且陆壳展布直到洋陆边界仍可揭示(Yan *et al.*,2014; Sun *et al.*,2018).

参照 Huismans and Beaumont (2011)的模拟和分类总结,南海陆缘应以II型破裂为主,但地幔破裂的位置尚需有效的探测手段揭示.根据同张裂－破裂前后岩浆量多少建议的新分类,南海东北部陆缘,如珠江口盆地中部陆缘和东部陆缘更多地表现出多岩浆类型,向西逐渐变为中岩浆和少岩浆类型.底侵岩浆的这种时空上的变化,姚伯初等(1983,1994a, 1994b, 1998)很早就提了出来,并认为与区域上伸展程度横向变化有关.根据数值模拟研究,南海岩石圈初始流变结构、伸展速率、岩石圈的富集情况等也都可能是影响陆缘结构和岩浆特征横向变化的重要因素(Pérez-Gussinyé and Reston, 2001; Pérez-Gussinyé *et al.*, 2006; Huismans and Beaumont,2011, 2014;Ros *et al.*, 2017).

地震观测表明,南海东侧陆缘的下地壳厚(万玲等,2009;曹敬贺等,2014)且软(Clift *et al.*,2002;张云帆等,2007, 2014; Sun *et al.*,2019a; Deng *et al.*,2020),而对应的华南陆缘电磁探测表明中地壳存在低速层.数值模拟表明(Li *et al.*,2019),如果变形前,强度大的上地壳和上地幔之间存在一定厚度的软弱中/下地壳,则拉张后发育较宽的超减薄陆壳(图7),超减薄陆壳的地壳厚度小,且热流值高,地壳底部由于被加热而呈韧性特征,且中间低粘度层的解耦作用,易导致共轭陆缘在单向拉张应力作用下伸展薄化得更明显不对称.这可以在一定程度上解释为何南海东部共轭陆缘南北不对称的问题.

根据磁异常条带识别,科学家们计算了南海洋壳扩张速率(Briais *et al.*,1993; Li *et al.*,2014).发现中央海盆和西北次海盆扩张初期的半扩张速率平均达到4 cm/a,而西南次海盆平均扩张速率约2 cm/a,如果该速率与伸展速率接近,那么东侧陆缘的拉张速率可能明显快于西侧陆缘.根据数值模拟研究,拉张速率是影响解压熔融岩浆产量的重要参数(Morgan *et al.*, 1987; Sotin and Parmentier,

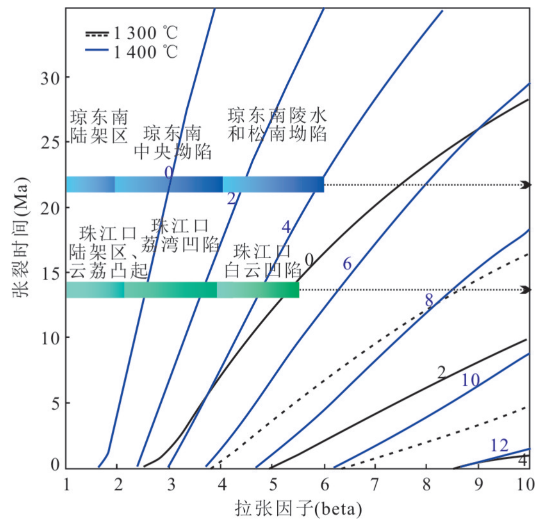

图8　南海北部陆缘盆地拉张产生岩浆量与张裂时间和张裂程度关系

Fig.8　The relationship between magmatic production and rifting period versus stretching factor in SCS.

底图据Bown and White(1995);珠江口盆地的拉张因子据张云帆等(2007, 2014)、Zhang *et al.* (2020b);琼东南盆地拉张因子据Qiu *et al.*(2013)

1989),慢速伸展相对于中速伸展将减少高达40%的解压熔融岩浆量.根据White and McKenzie (1989)以及Bown and White (1995)的计算结果,南海东北侧陆缘经历了大约14~15 Ma以上的拉张才发生破裂(~45~30/31 Ma),西侧陆缘经历了约22 Ma(~45~23 Ma)发生破裂,那么如果是正常的岩石圈(地幔温度约1 300 ℃)发生伸展,南海东西部陆缘产生的岩浆量都应较薄甚至缺失(图8).

如果是热地幔(温度约1 400 ℃)发生伸展,则珠江口盆地可产生最厚超过8 km的岩浆体,条件是岩石圈的拉张因子高达8以上,远远大于地壳薄化程度,因此壳幔薄化必须解耦且地幔薄化程度远大于地壳;琼东南盆地也可以产生岩浆,如果岩石圈与地壳薄化趋势一致,则琼东南可产生厚度近4 km的岩浆底侵.这与琼东南盆地未发现明显岩浆底侵高速层不一致(图4),且岩石地球化学证据不支持南海在同张裂－扩张早期具备热地幔特征(Yu and Liu,2020).那么南海东部陆缘珠江口盆地下厚度最大达10 km的底侵高速体成因机制是什么呢?

数值模拟显示,除了地幔温度,地幔富集程度也可以明显影响同张裂岩浆的生产率(Pérez-Gussinyé *et al.*,2006).南海新生代张破裂过程发生在中生代俯冲体系的基础上,且中新生代构造转换间隔较短,新生代的拉张作用可能受到

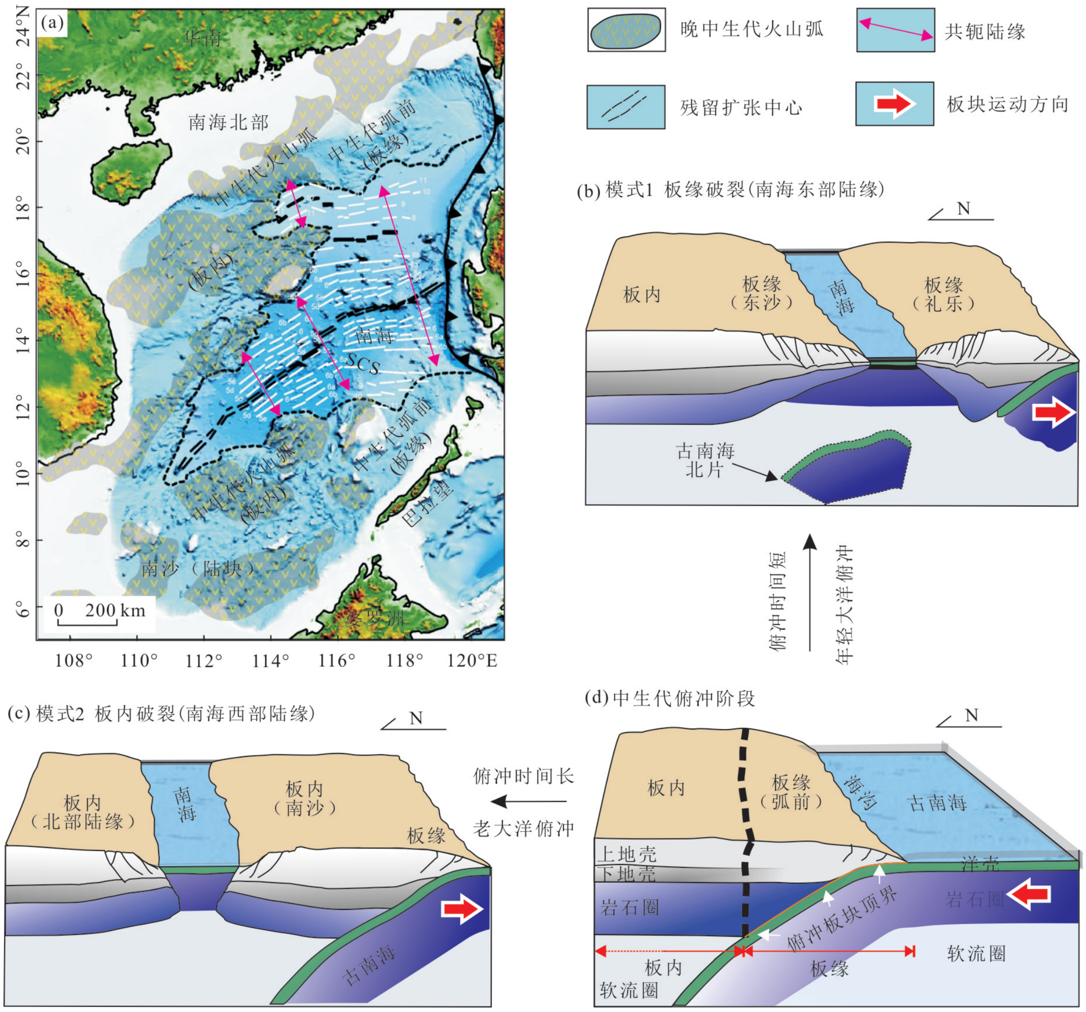

图 9　南海北部陆缘破裂位置及其与中生代俯冲系统关系分析

Fig.9　The breakup location of SCS and its relationship to Pre-Cenozoic subduction system

据 Li *et al.*(2020)修改.a. 南海共轭陆缘及其与中生代火山弧和弧前盆地的关系,其中东部陆缘破裂位置发生在中生代弧前盆地区,西侧陆缘破裂发生在火山之间;b. 根据数值模拟绘制的南海东部陆缘在弧前盆发生板缘破裂模式,板缘破裂常伴有俯冲板片的断裂和拆沉;c. 根据数值模拟绘制的南海西部陆缘沿火山弧/弧间发生板内破裂模式;d. 推测中生代俯冲阶段南海北部陆缘的状态,新生代时,沿着正常厚度的岩石圈破裂为板内破裂,沿着减薄的弧前区破裂为板缘破裂

中生代俯冲作用的影响(Li *et al.*, 2020). 根据对中生代火山弧展布的识别(Li *et al.*, 2008, 2018),南海陆缘破裂存在穿时空变化(Li *et al.*, 2020; Zhang *et al.*, 2020b; Lei *et al.*, 2020). 东侧陆缘破裂的位置位于弧前位置,岩石圈和地壳厚度小,属于典型的板缘破裂,西侧陆缘位于火山弧－弧后位置(Sun *et al.*, 2019a; Wang *et al.*, 2019b; Li *et al.*, 2020),属于板内破裂(图 9).

观测表明,俯冲带脱水的主要区域位于弧前到火山弧区,年轻的热板块在弧前会脱去大部分水(van Keken *et al.*, 2011). 根据数值模拟,对比南海陆缘特征,Li *et al.*(2020)提出南海东部陆缘为板缘破裂,推测与年轻洋盆俯冲或俯冲时间较短即发生了反向拖曳有关;而西部陆缘为板内破裂,推测与年老的洋盆俯冲或俯冲时间较长之后才发生反向拖曳有关. 因此笔者推测南海东部陆缘的弧前伸展破裂可能受俯冲流体影响强度更大,导致岩浆产率更高,从而导致南海东北部陆缘发育大范围岩浆底侵,且最大厚度达 10 km 以上.

4　结论

为了分析南海共轭陆缘的张破裂机制,本文在调研国内外最新研究进展的基础上,系统分析和整理了南海南北陆缘的地壳结构、岩浆活动特点,并对南海陆缘的分类归属和发育机制进行了初步探

讨,取得以下认识:

(1)岩浆在被动大陆边缘的张裂和破裂过程中起到决定性作用,早在岩石圈减薄之前陆缘的岩浆作用就发生了,拉张应力首先会导致岩脉沿着岩石圈内的裂缝上涌,高温岩脉的加入会导致岩石圈流变结构弱化,从而有利于岩石圈在相同的张应力下发生更大的变形.

(2)数值模拟揭示,由于流变性质的差异,地壳和地幔可能会发生差异伸展和破裂.当下地壳比较硬的时候,易形成地壳先破裂的I型陆缘;当下地壳比较软时,则无论什么拉张速率,陆缘都会以地幔先破裂的II型方式破裂.根据两类破裂方式的特点,南海陆缘应以II型破裂为主;伸展过程中地壳与地幔、甚至脆性上地壳和上地幔与韧性下地壳之间常常发生解耦,解耦作用常在不同流变结构的圈层之间产生空间,有利于岩浆沿水平方向的侵位,发生底侵.

(3)南海陆缘和海盆中发育有大量的岩浆活动,包括在陆缘下地壳的底侵高速体,同张裂—裂后—扩张后的岩浆侵入和火山喷发.底侵高速体在东侧陆缘较厚,最厚达10 km左右,P波速度较高;西侧陆缘下地壳高速体较薄甚至缺失,速度偏低;底侵高速体以及裂后岩浆活动主要分布在陆坡—洋盆区,与岩石圈强烈减薄相关;结合强制褶皱等同构造变形时间,笔者推测底侵高速体为同张裂成因.

(4)根据地壳结构与底侵岩浆的量,建议被动陆缘划分为5个子类:贫岩浆型、少岩浆型、中岩浆型、多岩浆型和富岩浆型.新的分类方案可以避免简单的二端元模型造成人们对贫岩浆型陆缘结构特征总结的困难和偏差,更好地界定不同类型陆缘张破裂特点和岩浆特征.根据新的分类方案,南海东部陆缘为多岩浆型,向西逐渐变为中岩浆型和少岩浆型.

(5)南海东西部陆缘底侵岩浆量的巨大差异除与伸展速率有关,可能还与东侧陆缘发生了板缘破裂,而西侧陆缘发生了板内破裂有关.南海东部陆缘的弧前伸展破裂可能受俯冲流体影响强度更大,导致岩浆产率更高,从而导致南海东北部陆缘发育大范围岩浆底侵,且最大厚度达10 km以上.

致谢:仅以此文献给姚伯初先生,纪念他在南海陆缘和海盆地壳结构和构造演化等方面做出的卓越贡献!

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