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南海地热研究综述

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摘　要　作为南海形成与演化地球动力学背景研究的一部分,南海大地热流测量一直是一项重要的工作.现有数据分析表明,南海热流值分布总体上反映了其区域大地构造背景.随着深水区油气勘探的重大发现,南海现今地温场的研究正不断深入,研究的区域亦从浅水区扩展到深水区,同时,基于油气勘探的需要,盆地热史恢复的工作逐步展开,热史恢复也得以进行.相关的地热研究成果已被用于预测构造带分布、约束构造演化史、探索深部地球动力学机制、评价油气生成潜力等诸多方面.然而,由于地理位置的特殊性以及原始资料的缺乏,南海地热研究还存在热流数据分布不均,岩石圈热结构及热史研究不深入,系统的区域对比研究缺少等问题.本文综述了国内外近些年关于南海地热研究的进展,并在此基础上对未来的研究提出了一些建议与展望.

关键词　南海,现今地温场,热史,综述

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Overview on geothermal investigation of the South China Sea

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Abstract　Heat flow is one of the important parameters for the study of geodynamic setting related with the origin and evolution of the South China Sea (SCS). Data analysis had demonstrated that the heat flow distribution could generally reflect the regional tectonic background. Along with the great achievement in oil and gas exploration in deep water area, the research on present geothermal field of the SCS is developing with the study area extended to the deep water area from the shallow water area. Moreover, the thermal history reconstruction is accordingly being carried out due to the oil and gas exploration requirement in deep water area. The geothermal research results of the SCS have been used for tectonic belts prediction, tectonic evolution constraint, geodynamic mechanism exploration, hydrocarbon generation potential evaluation and other aspects. However, there are still some defects such as uneven distribution of heat flow data, poor study on deep thermal structure and thermal history in the southern margin, lack of regional correlation study because of its particular geography and absence of data source. This study is aim to review the domestic and international research progress on geothermal field of the SCS, and put forward some suggestions and prospects on future study.

Keywords　South China Sea, geothermal field, thermal history, overview

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0 引 言

沉积盆地地热研究主要包括今、古地温场两方面,今地温场研究主要包括大地热流测量、岩石热物性参数的测试与分析、地温梯度和深部温度的展布特征以及岩石圈热结构等内容;古地温场的主要内容为热历史恢复[1].岩石圈热结构和温度分布直接影响着岩石圈及其结构层的物理化学性质与过程,同时也控制着岩石圈内的化学反应类型和速率,制约着岩石圈的发展与动力学演化[2,3];盆地热演化史(包括盆地热流史、地层温度史)的恢复不仅对烃源岩生烃期次、有机质成熟度史的确定和初次运移量及区带评价乃至圈闭评价等油气成藏描述具有不可或缺的意义,同时它也是研究盆地构造-热演化过程的一个重要方面[4,5].南海地区位于特提斯构造域和太平洋构造域两大构造域交互部位,经历了复杂的地质作用和演化过程,发育了丰富的地质构造,被国内外学者誉为“地球上最好的天然实验室”,是研究张裂大陆边缘形成演化与海底扩张的理想天然场所[6,7],而地热特征就是这些构造作用的共同反映.南海北部、西部和中南部分布着数目众多、类型各异的沉积盆地[8],石油地质条件优越,油气资源潜力巨大,其中南海北部陆架深水区已成为中国近海的主要油气产区之一[9-12].南海地热研究可以提供大量的热学参数(地温梯度、大地热流、岩石热导率、生热率等),有利于了解其构造演化和深部地球动力学机制;另外,可以揭示盆地热史,对探讨南海地区烃源岩的生烃历史、“烃灶”位置及其迁移特征,为油气资源预测和有利勘探区带评价提供科学依据.

1 地质背景

南海是西北太平洋边缘海中面积最大的海盆,位于欧亚板块、印度-澳大利亚板块及太平洋板块三者交汇处(图1)[13].南海海盆的扩张形成是新生代以来东亚地区的重大构造事件之一,而对于南海形成演化的动力学机制,许多学者提出了不同的观点[6,7,14-35].其中最具代表性有三种:

1)南海是与印度-欧亚板块碰撞挤出构造有关的走滑拉分盆地-碰撞挤出模式[32,36,37];

2)南海是与太平洋俯冲有关的弧后盆地-弧后扩张模式[14,17,18];

3)南海盆地的形成与地幔柱有关-地幔柱模式[38-41].

碰撞挤出模式能够很好地解释南海西北部NW

图1 南海区域构造位置图(据Honza E[53],有修改)

Fig. 1 Tectonic location of the South China Sea (revised form Honza E)

走向莺歌海盆地始新世-晚渐新世期间的断陷发育特征[18,42].然而,该模式存在两方面的缺陷.第一,挤出模式将欧亚板块视作塑性块体与实际不符[32,43];第二,碰撞挤出引起的左旋走滑运动与南海海底扩张的时间序列有待进一步考证,若挤出时间晚于南海打开时间则否认了其对海盆扩张的影响.最新的3D黏性流体模拟实验表明:印度-欧亚板块碰撞引起的地壳加厚主要被青藏高原所吸收,约20Ma后水平挤出才占主导地位,说明印支地块挤出只是对南海扩张晚期或对西部扩张有重要影响[44].弧后扩张模式的主要不足在于难以解释南海东部海盆近E-W向扩张脊与南北向的吕宋岛弧呈大角度相交,有悖于典型的弧后扩张盆地伸展应力模式.此外,对南海断裂性质与沉积地层方面的研究结果也与弧后扩张不符[22].对于地幔柱模式,多数学者认为它只是从理论上提供了动力来源,很难解释海盆内部复杂的构造现象[45,46].在不考虑动力来源的情况下,“海底扩张模式”[6,7,29]是关于南海成因的主要观点.目前对于该模式的争论主要集在缺少典型的线性磁异常条带[47]以及海底扩张期次、扩张时间的分歧两点上[6,7,48,49].

由于其特殊的大地构造背景及地球动力环境,中、新生代以来,南海曾经历了板块构造的俯冲、碰撞、挤压、走滑等一系列构造作用,形成了菱形海盆

及不同性质的构造边缘,发育了众多的新生代沉积盆地,即南海北部离散型陆缘盆地、西部走滑—伸展型陆缘盆地和南部伸展—挠曲复合型陆缘盆地[50,51].结合区域动力学背景分析,将南海新生代盆地形成演化大致划分为4个演化阶段,即扩张前初始裂陷阶段、同扩张强烈裂陷阶段、扩张后缓慢沉降阶段和扩张后快速沉降阶段[52],但每个盆地在扩张时间、沉降强度等方面有所不同.

2 研究现状

2.1 现今地温场研究

盆地的现今地温场研究主要包括大地热流测量、岩石热物性参数的测试与分析、地温梯度和深部温度的展布特征等内容.为了研究南海的起源、演化历史、大地构造属性及其形成的地球动力学背景,前人在大地热流测量方面做了大量工作,获得了大量钻井和海底热流探针数据[7,48,54-68]. He 等[69]首次对南海地区已发表的热流数据进行了系统收集和整理、分析,利用收集到的589个大地热流数据编制了南海大地热流图. Shi 等[70]收集整理了南海地区592个热流数据并进行了系统分析,研究了南海地区大地热流在平面上各构造单元的分布特征.这些热流数据主要分布于南海南、北陆缘区,少数分布于南海东部陆缘及海盆内,而南海西部陆缘、西沙-中沙群岛以及南沙地块热流数据更少.具有拉张背景的区域如北部陆缘、湄公盆地以及北巴拉望盆地具有中等偏高热流;海沟区热流相对较低,东部海沟区除台西南盆地外均为低热流区,而南部边缘东段古海沟区处于热恢复中;南部边缘西区因边界断裂的扭张及深部热源的异常补给而具高热流;属于剪切断裂带的西部陆缘也具高热流特征;中沙-西沙地区热流中等偏高,并由NW往SE方向增加,而南沙地区热流较低,约为60 $mW\cdot m^{-2}$;海盆的热流基本满足随洋壳年龄增加而降低的规律,东部次海盆实测热流与理论预测基本一致,而西南次海盆实测热流普遍低于预测值;在南海北部下陆坡区识别出一条高热流带,与海盆北缘断裂带位置基本一致.袁玉松[71]注意到地温梯度与计算深度密切相关,提出了用"归一化"来计算珠江口盆地与琼东南盆地的地温梯度,更准确地评价了这两个盆地的现今地温状态.张健等[3,72]和单竞男等[73]计算了南海北部大陆边缘热结构与深部温度,计算结果表明,虽然该区的热流背景很高,但地壳热流在地表热流中所占比例不超过35%,并且沿北部陆缘向南部中央海盆方向,所占比例逐渐衰减,计算区域各盆地的热结构也具有不均一性.此区各盆地热结构的不均一性与大陆架地壳减薄、软流圈热物质上涌等因素有关.莫霍面温度范围基本在600 ℃上下波动,最高温度可达726 ℃. Shi 等[74]通过重力异常拟合及地温场和流变性质的估算获得了西沙海槽深部热结构.张健等[75]依据南海中央海盆大地热流观测值及地壳结构资料,计算了海盆区热结构,得出的结论为,中央海盆洋壳层内垂向热流变化不大,但垂向温度变化较大,海盆区地幔热流在地表实测大地热流中所占比例高于80%,地壳下部热流在地壳总热流中所占比例小于20%,说明海盆的高热流背景主要来自地幔,而且下部地壳较薄.

总体来看,南海的今地温场研究主要集中于北部大陆边缘.南海的地热特征及深部热状态直接或间接地受控于其所处的构造环境,北部大陆边缘盆地属于"冷壳热幔"型盆地.

2.2 热史研究

盆地热史研究是盆地基础地质研究的重要内容之一,更是揭示盆地构造演化与油气运聚关系,选择和评价油气勘探目标地区的重要依据.目前为止,用于盆地热史恢复的方法概括起来分为两个大类:(1)适用于盆地尺度的古温标反演法;(2)适用于岩石圈尺度的构造热演化正演法.在盆地尺度和岩石圈尺度上进行热史恢复的方法是不同的,盆地尺度依赖于古温标,岩石圈尺度则强调盆地的成因模型[5,76].

2.2.1 *热史反演——古温标法*

采用古温标进行盆地热史恢复属于反演问题,其原理是利用古温标(如Ro、AFT等)所记录的热史信息,反演计算得到古地温、古地温梯度、古热流,从而重建盆地热史.古温标的种类很多,除传统的镜质体反射率Ro外,国内外已有不少学者开发了各种其他有机质古温标,如沥青反射率、牙形石色变指数[77]、镜状体反射率[78]、生物碎屑反射率[79]刚、有机质自由基浓度[80]、激光拉曼光谱[81]、伊利石的结晶度[82]等.新型低温热年代学温标〔包括裂变径迹和(U-Th)/He〕是近些年发展最快的领域.利用磷灰石、锆石和榍石裂变径迹恢复盆地的热历史也是目前最常用的方法,其中,磷灰石裂变径迹和镜质体反射率已成为目前最常用的两种古温标.

至今为止,关于用古温标方法进行南海区域热史的研究较少.汪辑安等[83]利用古温标数据Ro对南海北部陆缘的北部湾盆地、莺琼盆地和珠江口盆地的珠三坳陷的古地温梯度进行了研究,认为新生

代以来这三个盆地或坳陷的地温逐渐降低并在近期有所回升. 邓孝[84]等报道并分析了位于北部湾盆地、莺琼盆地和珠三坳陷 3 口钻井的 13 个样品磷灰石径迹测定结果,并认为北部湾盆地和珠三坳陷 30 Ma 以来未受过重大热事件,而莺琼盆地莺 1 井地区则在 16.3±2.55 Ma 经历过抬升事件,抬升幅度大于 1000 m. Yan Yi 等[85]运用裂变径迹(AFT)及(U-Th)/He 低温热年代学方法重建了华南陆缘新生代的剥露历史与热历史. 结果表明,华南陆缘新生代以来存在三期冷却史,区域南部(南海北部大陆边缘)开始冷却的时间晚于北部,最后一期冷却开始的时间介于 15～10 Ma 之间.

2.2.2　热史正演——构造-热演化法

构造-热演化模拟是在岩石圈的尺度通过求解瞬态热传导方程来研究盆地形成演化过程中的热历史和沉降史. McKenzie[86] 1987 提出的瞬时均匀纯剪模型是经典模型,其余模型多是针对不同地区或不同地质演化特征提出的在该经典模型基础上改造而成.

南海大陆边缘盆地,尤其是北部大陆边缘盆地新生代以来经历过多次拉张[48],现今温度可能是最大古地温. 由于古温标法只能反演出地层达到最高古地温时和之后的热史,早于达到最高古地温时刻的热史是不可能通过古温标反演得出的[5, 76, 87, 88],因此相对古温标反演法,构造-热演化正演在南海大陆边缘盆地热史恢复过程中可能适用性更广.

李雨梁等[89, 90]采用瞬时拉张模型分别对琼东南盆地崖北凹陷、南海北部大陆架西区(北部湾盆地,莺琼盆地和珠三坳陷)热演化史进行了研究. 认为崖北凹陷自渐新世以来经历了快速沉降-扩张-快速沉降三个运动阶段;陆架西区热流史存在渐新世与上新世两次热流高峰期,并且第二次的热流值(62.76～66.94 mW/m^2)略高于第一次(54.39～62.76 mW/m^2). 林畅松等[91, 92]应用多幕瞬时均匀简单-纯剪切模型对莺歌海、琼东南盆地进行了模拟计算,得到了这两个盆地浅水区的拉伸系数和热流史. 何丽娟等[69, 93]应用多幕非瞬时横向不均匀拉张纯剪切模型对穿过西沙海槽的一条剖面及莺歌海盆地进行了构造-热演化史研究、. 获得了该剖面不同阶段的拉伸系数和热流值;认为莺歌体系盆地新生代 3 期拉张使其逐步升温,5.2 Ma 以来盆地达到历史最高温时期,目前处于热流下降期. 宋洋[94]利用多期拉张应变速率法模拟计算了珠江口盆地和琼东南盆地热流史并认为珠江口盆地存在两次热流升高过程而琼东南盆地存在三期加热和两期冷却过程并在 5.4 Ma 以来存在一期快速沉降. 反映了南海北部陆缘存在多期次裂谷作用、热流升高的特征;"热沉降"阶段也非完全处于热衰减期,晚期也存在热流升高的加热事件,这些都有别于典型的被动大陆边缘盆地的热演化模式.

关于南海南部地区构造热演化史的研究鲜有报道. 刘振湖等[95]根据局部均衡回剥技术获得了万安盆地的构造沉降曲线,用现今地壳厚度作为条件限制,采用综合反演法将构造沉降曲线与岩石圈均匀拉张模式的理论构造沉降进行拟合,并且考虑地壳和沉积物中的放射性物质的生热量,研究了盆地的热演化史,并在此基础上进一步研究了其烃源岩成熟度史. 杨树春等[96]应用二维横向不均匀拉张模型对礼乐盆地构造热演化史进行了模拟,揭示了盆地两次连续拉张升温过程. 可以看出,南海构造热演化史的研究过程也是一个地质地球物理模型不断合理化、完善化的过程.

3　讨论与展望

近几十年来,国内外对南海进行了多方面的研究,但由于研究思路、方法、手段和研究程度的局限,在很多方面仍存在争议,比如南海扩张期次、扩张动力来源,西南次海盆扩张脊年龄、北部大陆边缘的构造属性等.

南海盆地现今地热特征是盆地热演化产物,热流分布特征总体上可以反映其区域构造背景,利用热流分布特征也可以对一些构造带进行预测,如南海北部下陆坡的高热流带就对应着一条地震活动断裂带[97]. 关于南海北部大陆边缘的构造属性,分歧的焦点是主动和被动之争. 有的认为南海北部陆缘盆地属于被动大陆边缘盆地[98-101]. 有的则认为南海北部的大陆边缘与典型的被动大陆边缘有差别,带有活动边缘的烙印[39]. 还有的认为南海北部大陆边缘构造活动性和岩浆活动较强烈,与典型的被动大陆边缘稳定性的特征不同,从而称其为"准被动大陆边缘"[102]. 南海北部大陆边缘低温热年代学研究表明其演化模式与典型的被动大陆边缘不符[85]. 关于西南次海盆扩张年龄一直具有争议,年龄范围 46 Ma[48]到 15.5 Ma[6],而该区域的高热流结果更支持后者[69].

南海地热学研究对于探索其构造演化过程及动力学机制意义重大. 另外,鉴于地层温度史(由地层埋藏史与盆地热流史共同决定)在烃源岩热演化(烃

源岩成熟度史)中的重要作用.南海地热学研究已被用于评价油气资源前景,寻找勘探有利区域[103-105].张功成等[106]提出的“源热共控”理论证实了南海地热研究在油气勘探中的重要性.

通过综述可以看出,南海地热研究已取得了不少成果,但仍存在以下问题:

1)热流数据分布不均.主要集中于南北陆缘,而东部陆缘、西部陆缘、海盆、西沙-中沙群岛以及南沙地块热流数据较少,无法进行系统、深入的现今热状态分析.

2)构造热演化模型及热史模拟结果的不一致性.地层埋藏史、拉张开始的时间、拉张期次、拉张模式、初始岩石圈和地壳厚度、热导率、生热率等诸多因素制约着热史模拟结果.以往的研究不仅参数存在明显差异,建立的地质模型也存在分歧,尤其是对拉张期次如何划分分歧较大,从而导致模拟结果互不统一.

3)南海中南部盆地的深部地热状态以及热演化史研究很少.

4)地热研究局限于单个盆地,缺乏系统、全区域对比分析集成.

今后的研究中,应该以盆地动力学、构造地质学、沉积地质学为指导,以南海及邻区新生代岩浆活动的年代学、岩石学和地球化学特征等方面的研究成果为约束,不断完善热史恢复的地质地球物理模型.加强对南海南部盆地的地热研究,在此基础上进行系统对比,从而探讨构造-热演化对成盆、成烃、成藏的控制机理,从盆地现今热体制和烃源岩热演化角度分析南海区域有利成藏单元.

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