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关于现代海底热液活动系统模式的思考

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摘要:现代海底热液活动往往与岩浆作用相伴生.传统的热液系统循环模式认为:海水沿裂隙(通道)下渗,被加热并与围岩发生水岩反应,萃取岩石中的金属元素,形成热液流体并上涌喷出海底,沉积生成多金属硫化物矿体.这一模式合理地解释了构成现代海底热液系统的 3 个基本要素:流体、通道和热源,与我们现今条件下所观察到的许多事实相吻合.然而,基岩渗透率、热液流体性质、热液生态系统和热液产物上的差异表明现代海底热液活动系统可能存在另一种注入式循环模式,即热液流体来自深部岩浆房流体和挥发性组分的直接注入.据此提出现代海底热液活动系统可能存在两种模式:一种是浅层循环模式,即传统的热液循环模式;另一种是岩浆后期热液注入模式(简称"注入模式").在岩浆作用强烈和构造裂隙发育的环境中,两种模式可能同时存在,形成双扩散对流循环模式.双扩散对流循环模式可以很好地解释现代海底热液活动研究中近期所发现的多种现象和事实.对弧后盆地而言,在研究其岩浆作用与热液活动时,还要考虑板块俯冲的构造背景和俯冲组分及陆壳组分加入等因素,同时构建了适用于弧后盆地海底热液活动系统的理论模型.

关键词:岩浆作用;海底热液活动系统;双扩散对流循环模式;弧后盆地;冲绳海槽.
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Reflections on Model of Modern Seafloor Hydrothermal System

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Abstract: Modern seafloor hydrothermal activity is generally accompanied by magmatism. Traditional hydrothermal system model hypothesizes that seawater penetrates through the rifts or cracks, then is heated and reacts with the surrounding rocks gradually leaching out metal elements from the rocks and resulting in the formation of metal-rich, acidic and reductive hydrothermal fluid. Subsequently, the heated fluid moves up along a series of fissures and erupts directly out of the ocean floor leading to precipitations of hydrothermal sulfides. This model reasonably accounts for the existence of fluid, channels and heat sources which are the three fundamental elements of modern seafloor hydrothermal system, and is in accord with many phenomena we have observed so far. However, differences in rock permeability, hydrothermal fluid properties, thermal fluid ecosystem and hydrothermal product indicate that there is possibly another injected circulation pattern for modern seafloor hydrothermal systems, which means the hydrothermal fluid is derived from the direct injection of fluid and volatile components from the deep magma chamber. Accordingly, it is inferred that there possibly are two models for modern seafloor hydrothermal sys-

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tems: one is the shallow circulation mode, namely the traditional mode of hydrothermal circulation; the other is a magmatic hydrothermal injection mode ("injection model"). In the environment of strong magmatism and well-developed fracture, two modes may exist simultaneously, and the double diffusive convection circulation model is proposed. The double diffusive convection circulation model can be used to explain a variety of phenomena and facts recently discovered in the study of modern seafloor hydrothermal system. Moreover, it is pointed out that the tectonic background of the subduction and the mixing of materials from both subduction component and continental crust are also considered in the study of the magmatism and hydrothermal activity in back-arc basin. Meanwhile, a theoretical model has been constructed for the sea-floor hydrothermal system in back-arc basin taking the Okinawa trough as an example.

Key words: magmatism; seafloor hydrothermal system; double diffusive convection system model; back-arc basin; Okinawa trough.

现代海底热液活动及其成矿作用的发现是地球科学发展史上的重要事件和里程碑,改变了人们对诸如生命起源、地球形成演化及陆上大型层状多金属矿床成因等重大科学问题的传统认识.现代海底热液活动是连接水圈、岩石圈和生物圈的重要纽带之一.根据质能守恒定律,地球系统作为一个整体,其内部各圈层之间无时无刻不在进行着物质与能量的交换或循环.自 20 世纪中期开始,随着海底扩张和板块构造理论的诞生和发展,人们逐渐认识到在一系列的海底构造活动过程中往往伴随有物质和能量的交换,这种交换的规模和程度一度成为地球科学界非常前沿的一个科学命题.Revelle and Maxwell(1952)和 Elder(2013)的开创性工作使人们意识到可以用海底热液循环来解释大洋地球内部的热散失,并在随后的调查研究中发现了海底热液活动存在的证据.当前,对现代海底热液活动及其沉积成矿作用的研究已成为国际地学界的热点之一,这是因为:(1)海底热液成因的多金属硫化物是与海底石油、锰结核、富钴结壳及天然气水合物同等重要的、具有深远开发远景的海底矿产资源,是人类发展所必需的战略性资源储备之一;(2)海底热液区的特殊生物群落是以化学合成作用为起点的、完全不同于陆地上依赖光合作用生存的生物,其特殊的基因资源对人类的生存发展及研究生命起源具有重要意义;(3)现代海底热液活动一直被认为是了解地球深部物质组成、结构及演化过程的"窗口"和"天然实验室",有关海底热液活动与沉积环境、构造背景和岩浆活动之间的关系也是人们当前研究的热点;(4)在现代海底热液活动区,热液流体与大洋不断进行着物质和能量的交换,对环境,特别是大洋热结构和海水化学组成的影响是直接且显著的;(5)对现代海底热液成矿作用的研究,有助于揭示陆地上古代可类比矿床的成矿机制,建立完善的找矿勘探理论和现代海底热液活动及其成矿作用理论(翟世奎等,2001;曾志刚,2011).目前,对现代海底热液活动及其产物的研究主要是对热液硫化物等热液产物、热液流体、热液柱及其热液成矿作用和热液区生物的研究.其中,构造背景、岩石、沉积物、洋壳的扩张速率和渗透性、断裂系统及深部的岩浆作用等均是影响热液活动的关键因素.本文主要讨论岩浆作用对现代海底热液活动系统的贡献.

1 现代海底热液活动的分布与传统的成因模式

众所周知,地球系统各圈层间的物质与能量差异,造成了彼此间的相互作用和物质与能量的传递或交换.地球内部是热的,而且以各种方式(热传导、热辐射和物质运动等)不断向外散热.其中,导致能量传递的物质运动主要包括岩浆作用、热液喷溢(热泉)以及地幔对流等,其中传导输送的热能占较大比重.地球不同圈层之间的物质交换有多种方式,仅就地球外部圈层(岩石圈、水圈和大气圈)而言,主要有洋壳的生成与消亡、火山喷发和流体(热液)循环 3 种形式.因此,岩浆作用和热液活动是地球系统中能量与物质输运的 2 种主要形式,我们所研究的海洋地质科学问题无不与此两大过程有关.

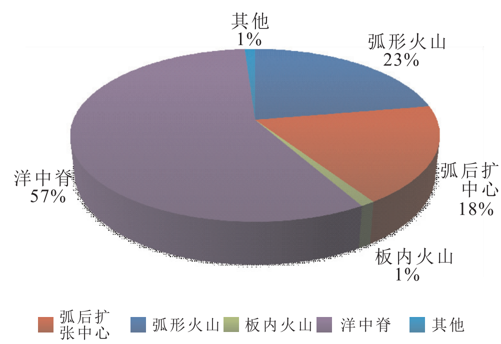

图 1 现代海底热液活动在不同构造环境中的分布

Fig.1 Distribution proportions of modern seafloor hydrothermal activities in different tectonic environments

据迄今所收集到的资料统计,在全球大洋中已发现了 649 个热液活动区或热液硫化物沉积区,主要分布在洋中脊(57.16%)、火山弧(岛弧)(22.34%)和弧后扩张中心(18.34%)等构造带上(图 1).就岩浆作用而言,大洋中脊构造带包含了 62%的全球岩浆储量和 73%的地表火山活动,火山弧(包括陆地和海底)的岩浆量约为全球岩浆储量的 26%(Perfit and Davidson,2000),而板内火山带的岩浆储量仅为 12%左右(Schmidt and Schmincke,2000).对比全球现代海底热液活动分布图与岩浆作用发育的火山带和洋中脊扩张中心,明显看出热液活动区的分布总是和岩浆作用相伴生,是一对“孪生兄弟”,除热点和岛弧之外,主要产生于张裂构造环境(图 2).海底热液活动最明显、最直观的特征就是高温热液流体喷出海底,形成黑烟囱,但受基底岩石(洋中脊玄武岩、超基性侵入岩甚至是陆壳组分)、温

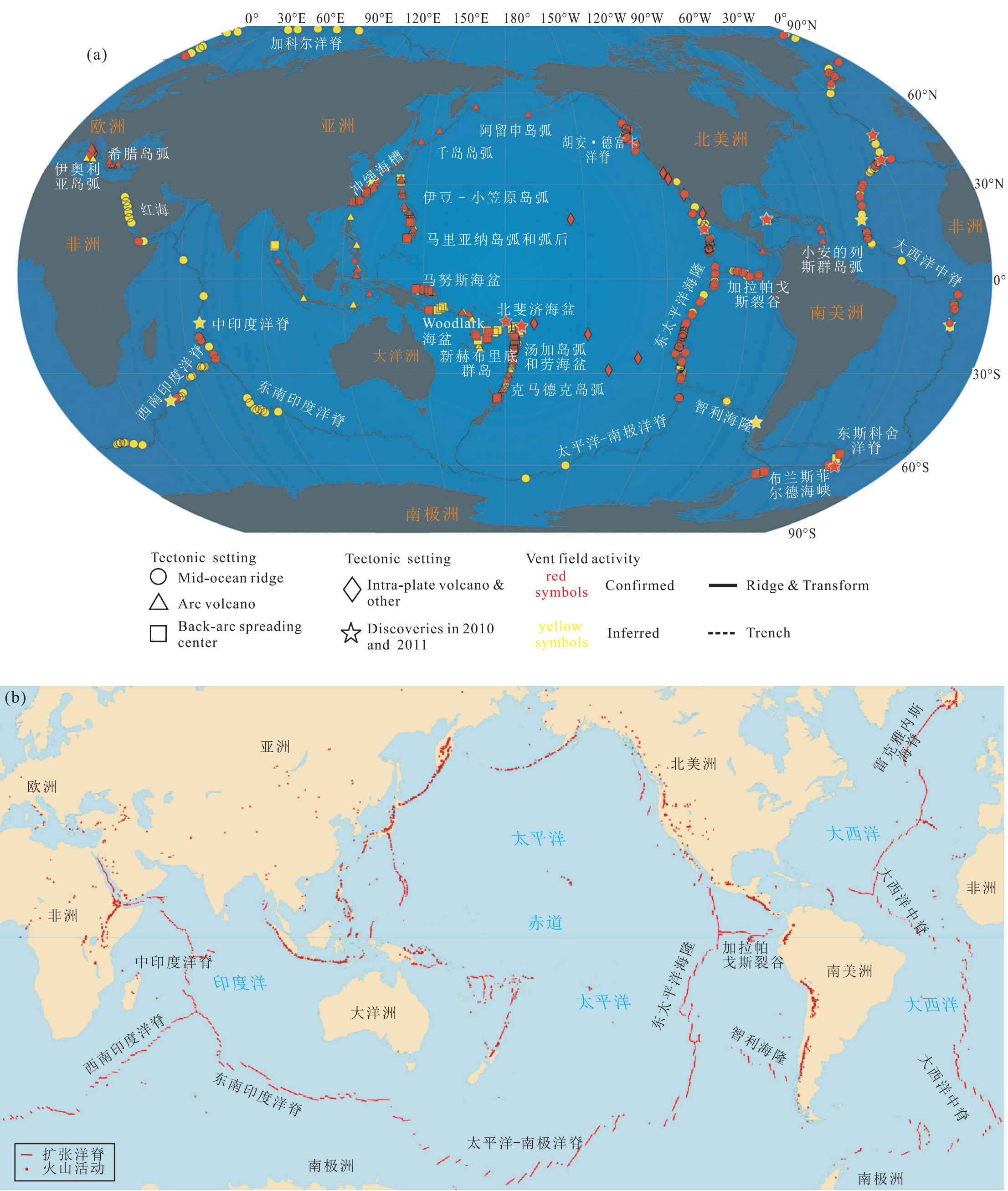

图 2　现代海底热液活动(a)与岩浆作用(b)在全球范围内的分布

Fig.2　The global distributions of modern seafloor hydrothermal activity and magmatic activity

b.来自 https://en.wikipedia.org/wiki/Volcano

度等因素的控制,海底还存在着白烟囱和弥散流等热液流体形式(Schultz *et al*.,1996;Gamo *et al*.,2004;von Damm and Lilley,2004;Kormas *et al*.,2006).不同构造背景下的热液活动及其热液成矿作用和热液产物差异明显(Hannington *et al*.,2005).通常情况下,在慢速扩张洋中脊发育的热液矿产规模普遍比快速扩张洋中脊的大(Hannington *et al*.,1995),例如慢速扩张洋中脊热液区的典型代表——TAG 热液区(Tivey,2007);洋中脊热液区形成的矿床往往富集 Cu 和 Zn,而弧后盆地的热液产物中 Pb 的含量明显较高.

尽管在不同的地质背景条件下,其洋壳扩张速率、水深、基岩组分、构造裂隙的发育程度以及热源的形态甚至是类型均有较大范围的变化,但以物质和热的交换为基础形成的热液流体喷出海底的过程和所形成的产物却具有很多的相似性.因此,前人在对各种已发现的海底热液活动及其成矿作用进行系统研究的基础上,总结了现代海底热液活动及其成矿作用模式.传统的海底热液活动系统模式(Scott and Hajash,1975;Rona,1976,1984;Franklin *et al*.,1981;Edmond and von Damm,1983;Scott,1985;Tivey,2007;李文渊,2010;曾志刚,2011)认为:冷的富氧海水沿裂隙下渗,在岩浆房上部受热并与周围岩石(地壳或上地幔岩石)发生反应,岩石中的大部分金属元素(如 Cu、Fe、Zn、Pb 等)逐步被淋滤出来,形成富含金属离子的、酸性、还原性热液流体;这种被加热了的流体受浮力作用向上运移,在渗透压力较低或裂隙通道处喷出海底,释放出热液流体;热液流体在接近或喷出海底时与周围冷的海水混合,形成热液柱,并由于温度、介质和氧化还原条件等的改变,发生热液成矿作用,沉淀生成多金属硫化物等热液产物(图 3).此外,海底热液系统的驱动力——热源可能并不是单一来自岩浆.海底橄榄岩与海水反应发生蛇纹石化作用,是一个典型的放热过程(Fyfe,1974),可能是超基性岩基底海底热液活动系统的热源之一(Rona *et al*.,1987;Barriga *et al*.,1998;Kelley *et al*.,2001;Schroeder *et al*.,2002).在低温热液活动系统中,橄榄岩的蛇纹石化作用可能是热液活动的主要热源,例如在 Lost City 等热液活动区(Kelley *et al*.,2001;Mével,2003).Lowell(2002)建立的热平衡模型也验证了上述观点.

Alt(1995)将现代海底热液系统划分为注入带、反应带和释放带;曾志刚(2011)则将热液系统简单的划分为海底表面以上和海底表面以下两个部分.传统的热液系统循环模型合理地解释了热液活动形成的 3 个基本条件:流体、通道和热源,与我们现今条件下所观察到的许多事实相吻合,似乎解决了岩浆作用与热液系统的相互关系,至今为大多数科学家所接受.但是,随着调查研究工作的拓展和深入,人们逐渐发现了许多传统的热液系统循环模型难以解释的现象或事实.

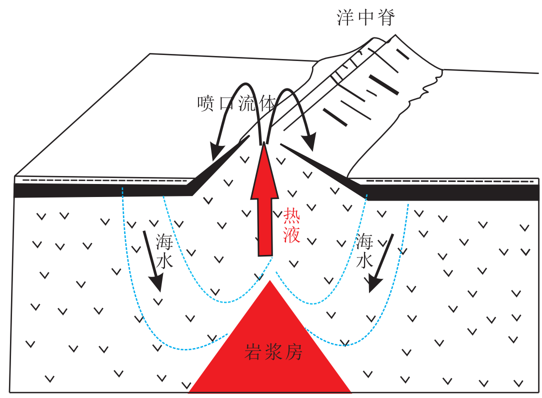

图 3 现代海底热液活动成因模式示意图

Fig.3 The growth model of the modern seafloor hydrothermal activity

2 有关热液循环系统的事实与矛盾

2.1 热液循环系统

洋壳的渗透性在海底热液循环过程中起着关键的控制作用.传统热液循环模型认为海水通过洋壳裂隙和断裂等构造下渗,后期形成的热液流体也是通过这些通道向上运移到海底表面.但是,大洋钻探、理论计算和实验模拟的结果表明,海底热液流体的循环可能并不是模型中提到的那样简单和理想.位于东太平洋哥斯达黎加断裂南部的 ODP 504B 钻井(图 4)钻探资料(Becker,1985;Newmark *et al*.,1985;Alt *et al*.,1989,1996;Pedersen and Furnes,2001;Teagle *et al*.,2003;Wolfgang *et al*.,2003;Guerin *et al*.,2008)表明,只有在海底之下约 200 m 范围内具有可供下渗海水流通的孔隙率,200~700 m范围内的火山岩由于孔隙被次生矿物充填而孔隙率下降,到 1 000 m 深之下,其孔隙率已降低至 <2%,如此致密的岩石中不可能有流体循环发生(Becker,1985;Newmark *et al*.,1985;Pezard,1990).传统热液系统循环模型成立的前提条件是海水沿高渗透率的玄武岩及裂隙下渗,穿过海底之下 3~5 km 深的洋底岩石(Andrews and Fyfe,1976;Bard,1984),并在岩浆房附近的高温条件下发生充

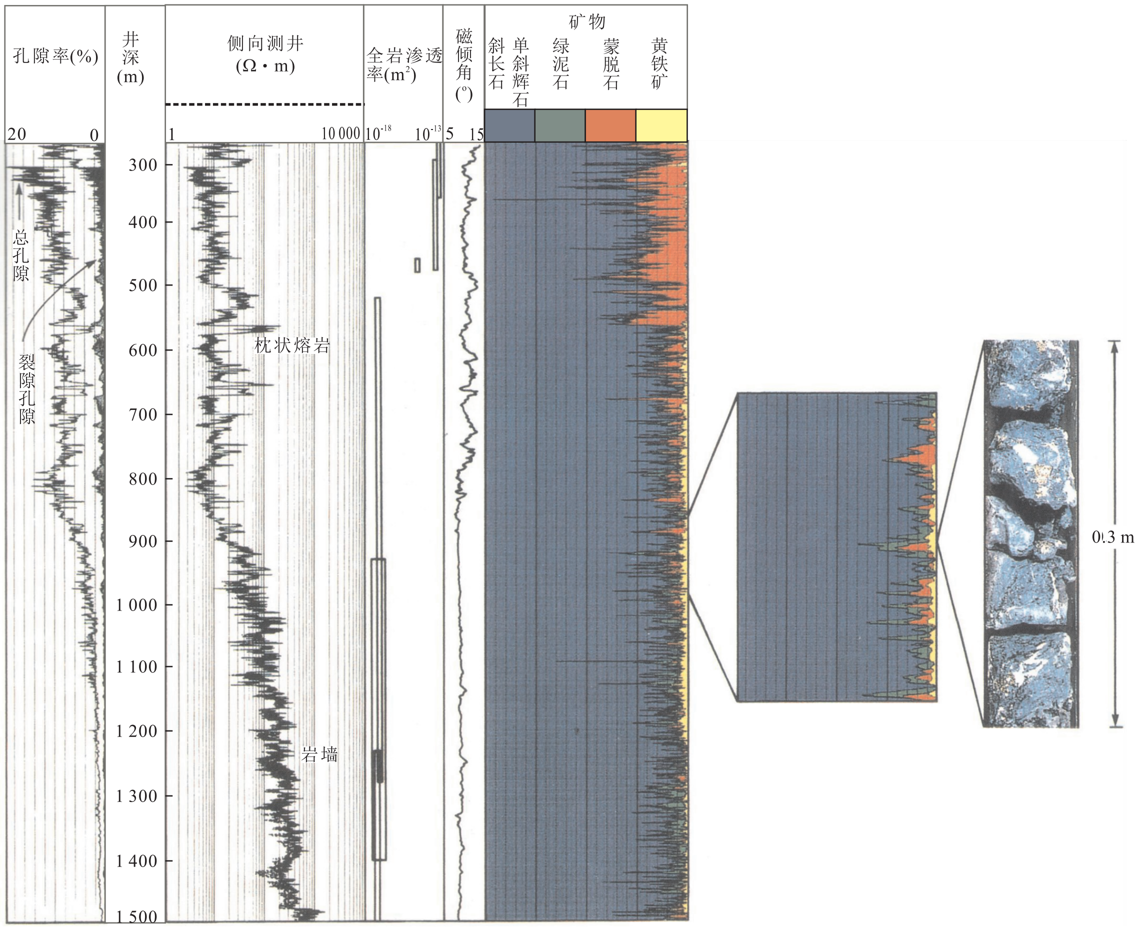

图 4　位于东太平洋海隆的 504B 深海钻孔岩心

Fig.4　The lithological profile of Hole 504B (ODP) located at the East Pacific rise

分的岩水反应,这与钻探所揭示的事实是相矛盾的.

2.2　岩水反应所需要的时间

在现代海底热液活动过程中,热液流体喷出海底向海水中不断释放物质和能量,尤其对地球能量的收支产生了重要作用.地球表面 70%的热量散失可以用洋壳中的热量迁移来解释(Sclater *et al.*, 1980;Converse *et al.*,1984),而热传导和海水热对流是洋壳热量迁移的主要机制(Anderson and Hobart, 1976; Parsons and Sclater, 1977; Sleep and Wolery,1978;Lister,1980).对比测量新洋壳获得的传导产生的热流值和板块降温理论模型获得的结果,可以发现两者之间差别较大,约为 2×10^{19}～8×10^{19} cal/a(Sclater *et al.*,1981),这部分热量主要是通过海底热液系统来传递(散失)的.Edmond *et al.*(1982)根据所测得的元素同位素数据,假设热液流体温度为 300 ℃左右,经过计算认为海水在洋中脊处下渗循环、发生水岩反应并喷出海底需要的周期大约为 8～10 Ma.洋中脊是海底扩张中心,尽管在不同大洋中脊的扩张速率(<1.4～18.0 cm/a;Dick *et al.*,2003)差别明显,但若按洋中脊半扩张速率的平均值(3 cm/a)计算,则海水下渗、经历水岩反应后再喷出海底时热液喷口要离开扩张轴 240～300 km,这与实际观测的事实——热液活动主要集中发生在洋中脊扩张轴附近是不一致的.

2.3　热液系统的地球化学特征

大量地球化学示踪研究结果表明,海底所喷出的热液应该是二端元液体混合的产物.首先,Sr 同位素组成是认识海底热液流体物质来源的重要指标之一,热液及其所形成的硫化物矿物的 Sr 同位素组成介于地幔和海水之间,其 $^{87}Sr/^{86}Sr$ 比值均低于海水,大部分位于靠近地幔及海底玄武岩端元.其次,对现场采得的大西洋 TAG 热液区热液流体的 Sr 同位素分析结果表明,$^{87}Sr/^{86}Sr$-Mn(Sr)曲线为简单的二端元混合直线,而非二端元混合后经混合同位素衰变演化后的双曲线(Faure,1987;图 5).再有,如图 6 所示,对比冲绳海槽热液区火山岩中岩浆包

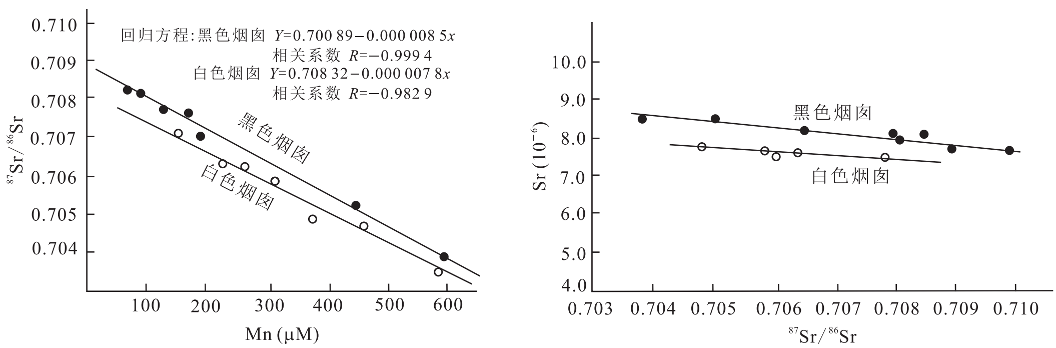

图 5 TAG 热液活动区黑色烟囱与白色烟囱热液的 Sr 同位素—元素相关图

Fig.5 Correlation diagrams of Sr isotopeic ratios and element contents in hydrothermal fluids from the black and white smokers in TAG hydrothermal field

裹体和热液成因矿物中流体包裹体各组分相对含量的平均值可以发现，在同一地区二者的组成几乎完全一致，不存在岩水反应程度不同的差异，说明岩浆与现代海底热液中的挥发性组分具有同源性，这是冲绳海槽岩浆作用对热液活动物质贡献的重要标志(于增慧，2000).还有，黑色烟囱和白色烟囱及溢散流似乎经历了不同的地质作用过程，好像不是同一个系统或过程所产生的热液流体(图 5).因此，海水下渗—岩浆房加热—高温岩水反应—上升—部分海水再混合—喷出海底—沉淀形成硫化物的传统模式很难解释：(1)漫长的岩水反应过程怎么会产生与地幔或玄武岩同位素组成几乎完全一致的端元热液？(2)怎样解释硫化物包裹体与岩浆岩矿物包裹体组成的一致性？(3)怎样解释黑、白烟囱及溢散热液流体之间的系统差异？

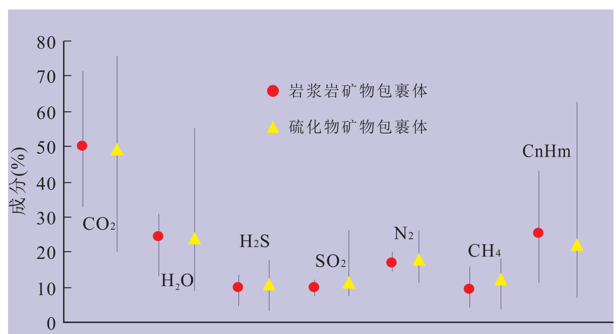

图 6 冲绳海槽热液区火山岩中矿物包裹体和热液成因矿物包裹体的成分对比

Fig.6 The comparisons of mineral inclusion compositions between volcanic rock and hydrothermal deposit from the Okinawa trough

据于增慧(2000)

2.4 热液生态系统

在 1977 年，科学家搭乘“Alvin”号载人深潜器在加拉帕戈斯裂谷水深达 2 500 m 的现代海底热液喷口周围发现了以管状蠕虫、蛤类和贻贝类为主的特殊生物群落(Corliss *et al.*，1979).海底热液生物群落的发现改变了人类对生物系统的传统认识，有利于进一步了解生命起源、生命进化过程和生命支撑系统等重大科学问题.

现代海底热液喷口生物群落在各大洋海底热液活动区均有分布.从构造位置和地质环境上看，热液喷口生物群落与热液喷口伴生，二者分布几乎一致.仅就环境的物理化学条件而言，所有热液喷口没有明显的差异，其生物群落也应该高度一致.但是，在不同大洋热液喷口区的生物群落却差别明显.在西太平洋弧后盆地热液活动区，热液喷口周围生物以 *provannidae*、瓣鳃类和贻贝类为主；在东太平洋海隆热液喷口区密集分布着大量的管状蠕虫；在大西洋中脊热液喷口附近生物则以虾和双壳类为主；而印度洋中的热液喷口生物以 *provannidae*、虾类和贻贝类为主(Hashimoto *et al.*，2001a，2001b；van Dover，2001；Tarasov *et al.*，2005；Zekely *et al.*，2006；Yoerger *et al.*，2007；王建佳，2012).环境条件(温度、压力、岩水反应、酸碱度等)相似的热液活动区为何发育有不同的生态系统？

2.5 热液硫化物的化学组成

热液硫化物是热液活动的重要产物之一，其矿物组成主要包括黄铁矿、黄铜矿、闪锌矿、磁黄铁矿、白铁矿、斑铜矿、纤锌矿和等轴古巴矿等.所有海底热液活动区硫化物的主要矿物组成基本相近，主要由 Fe、Cu、Zn 和 Pb 的硫化物组成，其中，黄铁矿(白铁矿)、闪锌矿(纤锌矿)和黄铜矿(等轴古巴矿)是最常见的矿物组合.但是，对分别采自东太平洋海隆、大西洋中脊和弧后盆地(如冲绳海槽)3 个著名热液活动区的硫化物中金属元素的丰度做统计分析，却

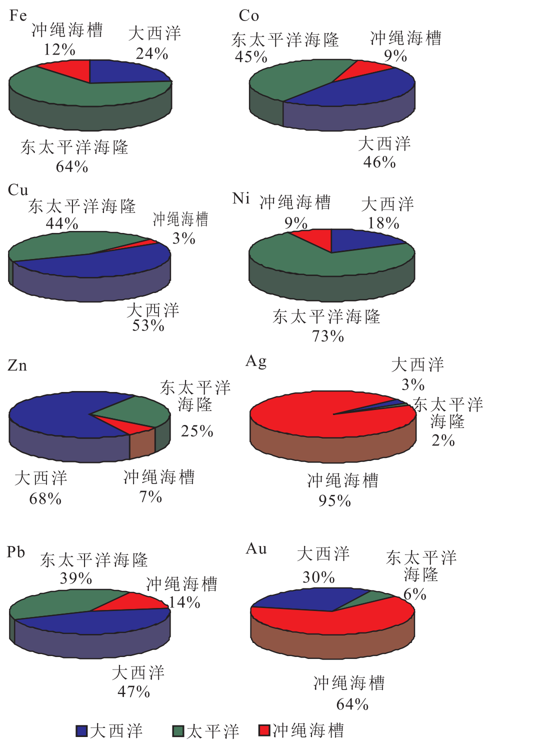

图 7　不同海区热液硫化物的元素相对丰度对比

Fig.7　The comparisons of relative abundances of elements in sulfides from different hydrothermal fields

发现不同热液活动区硫化物中金属元素的富集程度却是不一样的.在东太平洋海隆热液活动区,热液沉积物以富集 Ni、Fe、Co 和 Cu 为特征,可称为 Fe-Ni-Co 型硫化物;在大西洋热液活动区,热液沉积物以富集 Zn、Cu、Pb 和 Co 为特征,可称为 Zn-Cu-Pb 型硫化物;在西太平洋典型的弧后盆地(以冲绳海槽为例)热液活动区,热液沉积物中明显地富集 Ag 和 Au,可称为 Ag-Au 型热液硫化物(图 7).

弧后盆地热液活动区硫化物中富集 Ag 和 Au 在几个著名的弧后盆地热液活动区都有体现(翟世奎等,2001;曾志刚,2011),除冲绳海槽外还有 Lau 海盆、Manus 海盆和斐济海盆等,这些盆地的共性在于具有双峰式的火山活动,基底岩石除了玄武岩之外还有酸性的长英质火山岩.类似于热液生态学中的矛盾或问题:在环境条件(温度、压力、岩水反应、酸碱度等)相似的热液活动区,热液硫化物中富集的金属元素为何不同?

3　思考与探索

3.1　是否有源于地幔的热液参与热液循环系统?

绝大多数现代海底热液活动都与岩浆作用密切相关.位于热液系统深部的岩浆房作为热源加热流体、促使成矿流体对流循环是被普遍认可的观点.但岩浆作用是否为现代海底的热液成矿提供了物质来源则存在很多争议.首先提出此问题的当属 Yang and Scott(1996),他们在对马努斯海盆火山岩包裹体的研究中,找到了熔岩中存在岩浆流体(magmatic fluid)的直接证据,认为富含金属元素的岩浆流体很可能为海底热液系统提供了物源.众所周知,岩浆作用自产生后的上升过程是一个结晶分异演化过程,残余岩浆中将逐渐地富集挥发性组分,最后会导致岩浆后期热液的形成.从理论上讲,不能排除岩浆作用后期热液直接加入海底热液系统或直接喷出海底的可能性.

上述观点成立的前提是地幔中要有“水分”.地幔中是否有“水”是争论已久的老的科学问题,人类围绕这个问题展开了一系列的科学调查和实验模拟,越来越多的研究结果证明地幔中是有水的.

首先,来自地幔甚至更深处的岩浆是含水的.虽然地幔主要造岩矿物即橄榄石、辉石、石榴子石及其高压变体都是名义上的无水矿物,但是,通过红外光谱、离子探针、金属还原真空抽取、核反应分析和核磁共振等分析方法对上地幔橄榄岩包体矿物的研究,可以确定地幔矿物相都不同程度地含有水(Rossvra and Svrvrn,1990;Bai and Kohlstedt,1992;Bell,1992;Bell and Rossman,1992;Kohlstedt *et al.*,1996;Rossman,1996,2006;Peslier,2010;Yang *et al.*,2010;Withers *et al.*,2011;Zhou *et al.*,2013;Doucet *et al.*,2014;Ragozin *et al.*,2014).高温高压实验也为地幔水的存在提供了更多的证据(Yamamoto and Akimoto,1977;Liu,1987;Finger and Prewitt,1989;Withers and Hirschmann,2008;Karato,2010;Yang *et al.*,2014).综合实验模拟和地质与地球物理研究结果可知,地幔过渡带可能是最富集水的圈层(Inoue *et al.*,2010;Xia *et al.*,2010;Zhou *et al.*,2013;Zhu *et al.*,2013;Bizimis and Peslier,2015;Ohtani,2015),而这一圈层正是海底岩浆的主要源地.

其次,地下软流圈的存在若是在无水干系统条件下是难以解释的.板块构造理论中最重要的内容就是地幔对流造成塑性软流圈之上的刚性岩石圈板块运动(Hirth and Kohlstedt,1996;Höink *et al.*,2011;Karato,2012).然而,一系列的实验模拟和理论模型都证明,软流圈在无水干系统条件下是很难存在的.水在上地幔的塑性变形和演化过程中具有

非常重要的作用(Wang,2010),软流圈的特性普遍与地幔岩中含有水有关(Hirth and Kohlstedt,1996;Evans *et al*.,2005;Karato,2012).例如,水的存在可以在很大程度上降低上地幔物质的熔点和粘滞度(Hirth and Kohlstedt,1996,2003;Hirschmann,2006;Karato,2010;Wang,2010).实验结果表明,在压力为 300 MPa 且有水存在的条件下,橄榄岩的粘滞度系数最大可以降低 140(Hirth and Kohlstedt,1996).早在 20 世纪 60 年代末,科学家就通过实验证实地幔榴辉岩或橄榄岩只有在有水存在的前提下,才可以解释低速带的成因(Kushiro *et al*.,1968;Ringwood,1969;Lambert and Wyllie,1970).Hill and Boettcher(1970)的辉长岩－水－二氧化碳实验和 Kushiro(1970)的橄榄岩－水实验进一步证明了这个解释的有效性和准确性,并被广泛认可.挥发性组分(主要是 H_2O 和 CO_2)在软流圈中富集并促使软流圈物质发生初熔而产生岩浆(Green and Liebermann,1976;Wallace and Green,1988;Presnall and Gudfinnsson,2005;Green *et al*.,2010;Sifré *et al*.,2014).

再有,在热液喷口周围及海底之下均分布着密集的微生物群落,目前我们对海底之下的深部生物圈还知之甚少.对海底以下深部极端高温环境中的微生物活动的研究已成为当代生命科学的重要课题之一.近十几年的大洋钻探和海底热液活动研究发现了海底"深部生物圈"、"暗色生物链"等生态系统.例如,ODP Leg 201 航次在太平洋东部 5 000 m 的深海钻孔岩心中发现了微生物的存在,丰度可达 10^6 cm^{-3}(Jørgensen and D'Hondt,2006);在东太平洋海隆的玄武岩中也生存有大量的微生物,丰度为每克熔岩中含有 $3\times10^6\sim1\times10^9$ 个微生物(Santelli *et al*.,2008);在大西洋海底以下 1 626 m 的白垩纪地层里也存在着微生物(Roussel *et al*.,2008).以上事实证明在海底之下千米深的范围内仍有生命生存,这颠覆了人们对于生命起源的传统认识,甚至有人提出"地球生命来源于地球深处(地幔)"的观点.所有这些生物的存在都离不开有水的环境.

还有,越来越多的证据表明地球生成的初始可能带有大量的水.关于地球上水的起源目前主要有两大说法:自源说和外源说(李雨新,1984).外源说认为地球上的水来自外太空(贾绍凤,2015).彗星长期以来一直被认为是地球上水的重要来源,但 2014 年底当欧空局在 2004 年发射的"罗塞塔"探测器抵达 67P/丘留莫夫－格拉西缅科彗星(简称 67P 彗星;Cottin,2015)后发现事实并非如此.通过地球水与 67P 彗星水的对比可以发现,67P 彗星的氘氢比是地球上的 3 倍,由此可确认地球上的水并非来自彗星(赵海斌等,2005;Altwegg *et al*.,2014;谢懿,2016).降落到地球上的陨石通常都含有一定量(0.5%～5.0%)的水,但陨石数量之少及缺乏把陨石中的水变成液态水的物理化学过程使得地球上的水来源于陨石的观点基本不成立(李雨新,1984;贾绍凤,2015).而太阳风带来氢和氧结合形成水分子的量与地球表面现有的水储量相比不过是九牛一毛(贾绍凤,2015).因此,外源说的依据不足.自源说则认为地球上的水来自于地球本身(李雨新,1984;贾绍凤,2015).Hallis *et al*.(2015)对 Baffin 岛和西格陵兰具有地球初始同位素组成的苦橄质熔岩的橄榄石斑晶中熔体包裹体进行了 H 同位素分析,其结果表明熔体包裹体的氢同位素组成(δD) 可以低至－218‰,代表了深部地幔源区的上限值.结合源区混合模型,该深部地幔具有极低的地球初始 H 同位素组成(－870‰),这种极低的初始 H 同位素组成基本排除了后期陨石撞击带来水的可能性.现在越来越多的证据表明地球在形成时是自身含水的.Pearson *et al*.(2014)对新发现的尖晶石和橄榄石样品进行了分析,其结果充分证明地幔上下层之间的过渡带存在有水,而且按照岩石中的水存在的比例,水资源储量相当丰富,甚至有望超过全球海洋总水量之和(Pearson *et al*.,2014).

另外,俯冲到地幔中的洋壳可以带入水(Ohira *et al*.,2014).俯冲带中的岩石和矿物中都含有一定量的水,可能以水分子或者结构羟基的形式存在(Zheng and Hermann,2014),水从俯冲洋壳迁移到地幔主要受洋壳中含水矿物的稳定性支配(郑永飞等,2016).俯冲带水迁移是水进入地球内部的主要方式,这一过程不仅在很大程度上影响了地幔的若干物理化学性质,而且改变了地幔的熔融温度和流变学性质(Hirth and Kohlstedt,1996;Mei and Kohlstedt,2000a,2000b;Karato and Jung,2003;Evans *et al*.,2005;Green *et al*.,2010;Wang,2010;Karato,2012;Sifré *et al*.,2014).俯冲带是地壳物质循环和挥发性组分进入地幔的关键区,同时是熔体抽取、新生地壳生长并最终形成大陆地壳这一系列过程的起点(Turcotte and Schubert,2014).水在俯冲带岩浆活动中具有重要作用,与地震活动之间也存在着成因联系(Wyllie,1988;Peacock,1999;Hacker *et al*.,2003;Abers *et al*.,2006).脱水作用是在

俯冲板块进入弧下一定深度时，由于角闪岩相向榴辉岩相转变时角闪石分解而释放出水的过程，这些水引发了上覆地幔楔的部分熔融（郑永飞等，2016）．总而言之，在地球系统科学视野下，越来越多的证据指向地球深处（地幔，特别是软流圈）是有水的．地幔中有水，就有源于地幔的岩浆作用后期热液加入热液系统的可能性，就可以解释前述诸如海底渗透率不高、端元热液化学性质和同位素组成等许多难以解释的科学事实．

3.2　自然界中是否存在两种热液系统循环模式？

基于上述存在的事实和矛盾，作者认为在自然界中存在两种热液系统循环模式：一种是传统的浅层循环模式，可称为"海水循环模式"；另一种是岩浆（后期）热液注入模式，简称为"注入模式"．海水循环模式可以简单地分为海水下渗、流体与周围岩石发生水岩反应并被加热和热液流体喷出海底 3 个阶段（Germanovich *et al*．，2000；Lowell and Germanovich，2004；Gosnell，2006），这也是传统的海底热液系统循环模式．注入模式中的热液流体来源于深部岩浆房岩浆作用后期热液及挥发性组分的直接释放（Yang and Scott，1996；Herzig *et al*．，1998；Kim *et al*．，2004），即在现代海底热液系统中，下部的岩浆房不仅为其提供了热源保障，也是其热液产物的物质来源．Large（1992）早在 1992 年就通过对澳大利亚火山成因块状硫化物矿床的研究证明，Pb、Zn 和 Ag 等易溶元素主要来自于热液的淋滤作用，而 Cu、Bi、Sn、Mo 和 Te 等难溶元素则主要直接来自岩浆，Au 元素的富集可能是两种过程共同作用的结果．另外，热液系统中所富集的 S 元素则可能大部分源于岩浆，少量来自海水中硫酸盐的还原（Herzig *et al*．，1998）．

在岩浆作用强烈、构造裂隙发育的环境中，两种模式可能同时存在，形成双扩散对流循环模式（图 8）．双扩散对流循环模式可以解释前述所有传统模式难以解释的事实：（1）洋壳低渗透率问题——热液循环只发生在洋壳上部高渗透率岩层，该岩层裂隙发育，可为热液循环提供良好的流体通道；（2）海底高温热液活动集中发生在洋中脊轴部——洋中脊作为新生洋壳的发源地，岩浆作用强烈，岩浆房沿中脊扩张轴广泛分布（尤其是在海底热液活动最为发育的东太平洋海隆），各种断层及构造裂隙十分发育，这里的热液活动以岩浆后期热液注入模式为主；（3）热液或热液沉积物与地幔或玄武岩成分一致的端元热液——因为热液流体本身来自地幔岩浆；（4）

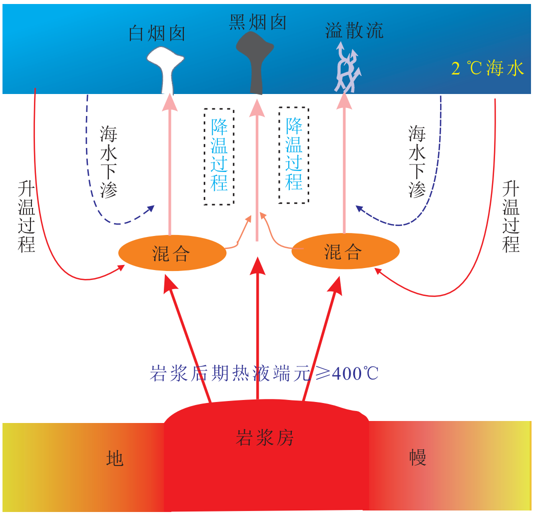

图 8　海底热液活动的双扩散对流模式

Fig.8　The double diffusion convection model for modern seafloor hydrothermal activity

硫化物包裹体与岩浆岩矿物包裹体组成一致——因为两者具有相同的物源；（5）黑、白烟囱及溢散流体之间的系统差异——可能是由两种不同模式和物源造成的；（6）热液生态和富集元素的区域性差异——可能是由地幔物源的不均一性造成的．

3.3　弧后盆地（以冲绳海槽为例）的岩浆作用与热液活动

俯冲带是地球上板块消亡并同时产生岩浆作用的关键地区之一，其岩浆作用涉及到地壳与地幔的物质交换和相互作用，在壳幔物质平衡中扮演着重要角色（Bourdon *et al*．，2003）．在西太平洋大陆边缘分布有一系列边缘海盆地，其成因是西太平洋海底板块向欧亚大陆板块俯冲导致陆壳拉张扩展而形成的，即弧后扩张作用的结果．弧后扩张作用的起因是板块俯冲打乱了软流层地幔的平衡，导致"次生地幔对流"，进而引发弧后区地幔物质上涌所致（翟世奎等，1997）．弧后扩张作用在形成具有洋壳性质的弧后盆地的同时，伴随有强烈的岩浆作用和热液活动．弧后盆地特殊的地理位置、张性应力场、强烈的岩浆作用、高热流值、普遍的热液活动等一系列的特征都说明这样一个事实："板块俯冲－弧后扩张－岩浆作用－热液活动"这是一个必然有着内在成因联系的系统．弧后盆地内的岩浆作用不仅是连接板块俯冲和弧后扩张作用的纽带，而且是热液活动的能量来源，在一定程度上也是其物质来源．

作为一个典型的弧后盆地，冲绳海槽、琉球岛弧和琉球海沟一起构成了一个完整的沟－弧－盆体系

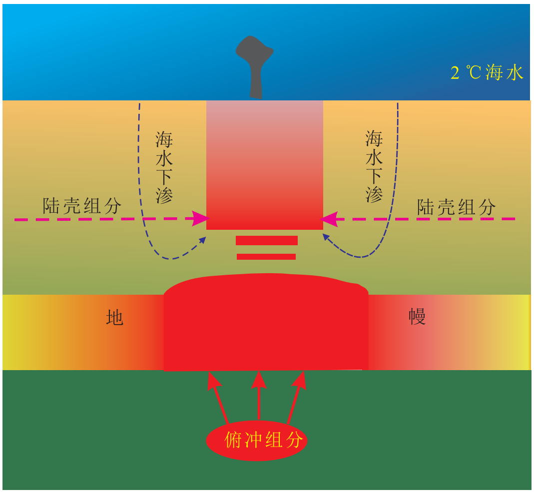

图 9　冲绳海槽岩浆作用与热液活动关系模式

Fig.9　The model diagram of relationship between magmatism and hydrothermal activity in the Okinawa trough

(翟世奎等,2001).冲绳海槽特殊的地理位置和一系列突出的特征,使其成为研究弧后盆地岩浆作用与热液活动最为理想的场所.俯冲带岩浆物质是多源性的,地幔楔物质熔融是俯冲地区岩浆物质的主要来源,但俯冲的古老洋壳物质以及深海沉积物对于岩浆也有着重要贡献,在一些俯冲地区岩浆甚至遭受到陆壳物质的混染(李怀明等,2009;国坤等,2016).翟世奎等(1997)认为由于俯冲的"水化洋壳"的失水作用使得其上的地幔或下部地壳物质的熔点大大降低,导致在冲绳海槽中部和东部地下 15 km 以下的地幔物质部分熔融,产生橄榄拉斑玄武质岩浆,而在海槽中部地壳下结构层(7～15 km)中物质部分熔融产生少量安山质岩浆,即在冲绳海槽地下存在有双层岩浆房结构,并且二者之间在中部有岩浆通道.浮岩的 Rb、Sr 和 O 同位素资料表明冲绳海槽的岩浆物质来源于地幔,同时也受到了地壳物质的混染(翟世奎等,2001).另外,富含碳酸盐的沉积物可随俯冲板片进入到岩浆中,导致岩浆中的 CO_2 过剩,这些过剩的 CO_2 可通过岩浆去气作用或岩浆结晶演化后期所形成的热液进入热液流体循环系统,最终使喷出的热液流体具有较高浓度的 CO_2(达到 209 mmol/kg)及高 $CO_2/^3He$ 比值(Glasby and Notsu,2003;Tsuji *et al*.,2012).岩石类型分布和地球化学特征表明冲绳海槽岩浆作用存在区域性差异,这种差异除了受地幔的熔融程度的影响,更与俯冲板块物质的加入有关,且南部玄武岩岩浆受俯冲组分影响的程度要高于中部,这可能受控于俯冲板块的深度(南部:100～150 km;中部:约 200 km)(宗统等,2016).特殊的板片俯冲地质背景、岩浆作用、基岩的不同及沉积物的加入等使得弧后盆地内的热液活动与大洋中脊处的热液系统有所不同,所形成的热液产物也有着明显的区别.因此,我们在研究冲绳海槽的岩浆作用与热液活动时,除考虑前述两种热液活动模式之外,还要考虑板块俯冲的构造背景和俯冲组分加入这一因素(图 9).

4　结论

(1)海底热液活动与岩浆作用是一对相伴而生的"孪生兄弟",岩浆作用不仅为海底热液循环系统提供了能(热)源,而且是热液成矿作用的物源之一.

(2)现代海底热液活动系统存在两种模式,一种是浅层循环模式,即海水下渗－岩浆房加热－高温岩水反应－富金属酸性热液上升－喷出海底－沉淀生成硫化物的传统模式;另一种是岩浆后期热液及挥发性组分注入热液活动系统的模式,简称"注入模式".在岩浆作用强烈,构造裂隙发育的环境中,两种模式可能同时存在,形成双扩散对流循环模式.双扩散对流循环模式可以很好地解释现代海底热液活动研究中近期所发现的多种现象和事实.

(3)在研究弧后盆地岩浆作用与热液活动时,还要考虑板块俯冲的构造背景和俯冲组分及陆壳组分加入等因素.

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