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热液烃分子地球化学特征及其成藏启示

朱必清[1,2],刘全有[1],许汇源[2,3],朱东亚[2],王静彬[2],张　驰[3]
(1. 北京大学 能源研究院,北京 100871;2. 中国石化 石油勘探开发研究院,北京 102206;3. 中国科学院 地质与地球物理研究所,北京 100191)

摘要:岩浆-热液作用是驱动地球多圈层物质循环与能量交换的关键动力,对油气及其他关键矿产资源的形成与分布具有重要控制作用。系统对比分析了全球深海与陆地岩浆-热液系统的烃类分子地球化学特征,研究了热液形成烃与热液改造烃的成因机制,结合地质背景探讨了热液活动对油气运聚与保存的影响。研究表明,热液烃的分子指纹较为复杂,与低成熟度、生物降解、硫酸盐热化学还原反应(TSR)和燃烧成因烃类特征存在不同程度的重叠。岩浆-热液环境导致油气成因多元化,短链烃可能是费托合成等非生物来源,长链烃主要来自微生物代谢及有机质热解。岩浆-热液作用具有显著的控藏效应,岩浆-热液流体可携带和驱动深层烃类沿断裂通道向浅部运移成藏,其高温与强氧化性会显著蚀变原始油气藏,伴随的巨量甲烷释放则会改变油气藏的相态分布。"热液控藏"机制是指沉积盆地中岩浆-热液活动强度和流体性质与断裂通道、盖层条件和古油气藏在时-空上的耦合配置,它们共同决定了现今油气的富集规律与分布格局。在岩浆-热液活动强烈区,油气勘探应系统评估岩浆-热液流体的改造作用,通过深化多因素耦合下的控藏机理研究,为该类复杂领域的勘探实践提供理论指导。

关键词:分子标志物;有机-无机相互作用;深部热液流体;热液控藏;超深层油气;塔里木盆地
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Molecular geochemical characteristics of hydrothermal hydrocarbons: Implications for hydrocarbon accumulation

ZHU Biqing[1,2], LIU Quanyou[1], XU Huiyuan[2,3], ZHU Dongya[2], WANG Jingbin[2], ZHANG Chi[3]
(1. *Institute of Energy*, *Peking University*, *Beijing* 100871, *China*; 2. *Petroleum Exploration and Production Research Institute*, *SINOPEC*, *Beijing* 102206, *China*; 3. *Institute of Geology and Geophysics*, *Chinese Academy of Sciences*, *Beijing* 100191, *China*)

Abstract: Magmatic-hydrothermal processes represent a pivotal driver behind cross-sphere material circulation and energy exchange within the Earth system, exerting a significant control over the formation and distribution of critical mineral resources such as hydrocarbons. In this study, we systematically compare the molecular geochemical signatures of hydrocarbons from global deep-sea and terrestrial magmatic-hydrothermal systems. Accordingly, the formation mechanisms of hydrocarbons of hydrothermal origin and those formed by hydrothermal reformation are investigated, and the influence of hydrothermal activity on hydrocarbon migration, accumulation, and preservation is explored in combination with geological settings. The results indicate that hydrothermal hydrocarbons exhibit complex molecular fingerprints, which partially overlap with the characteristics of low-maturity and biodegraded hydrocarbons, hydrocarbons formed by thermochemical sulfate reduction (TSR), and hydrocarbons of combustion origin. The magmatic-hydrothermal environments give rise to diverse hydrocarbon origins. Specifically, short-chain hydrocarbons might have an abiogenic origin, such as Fischer-Tropsch synthesis, while long-chain hydrocarbons are primarily formed by microbial metabolism, as well as the pyrolysis and cracking of organic matter. Magmatic-hydrothermal processes exert significant control over hydrocarbon accumulation. Magmatic-hydrothermal fluids can carry and drive deep hydrocarbons to migrate upward along faults, facilitating their accumulation in shallow parts. The high temperatures and strong

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第一作者简介:朱必清(1997—),男,博士研究生,油气地球化学与多圈层相互作用。**E-mail:**zhubq@stu. pku. edu. cn。
通信作者简介:刘全有(1975—),男,教授,油气地质与地球化学。**E-mail:**qyouliu@sohu. com。
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oxidation properties of these fluids can significantly modify pre-existing hydrocarbon reservoirs, while the associated release of substantial methane can change the phase distribution of hydrocarbons in reservoirs. The mechanisms behind magmatic-hydrothermally controlled hydrocarbon accumulation refer to the spatiotemporal coupling of the activity intensity and properties of magmatic-hydrothermal fluids with fault pathways, cap rock conditions, and paleo-hydrocarbon reservoirs in sedimentary basins. These factors jointly determine the present-day patterns of hydrocarbon enrichment and distribution. In regions characterized by intense magmatic-hydrothermal activity, hydrocarbon exploration must fully integrate the effects of fluid interactions. A deeper understanding of multi-factor coupled reservoir-controlling mechanisms is essential to effectively guide exploration practices in these complex geological settings.

Key words: biomarkers, organic-inorganic interaction, deep hydrothermal fluids, hydrothermal controlled hydrocarbon accumulation, ultra-deep reservoirs, Tarim Basin

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岩浆-热液作用作为行星演化的核心地质营力，驱动着岩石圈-水圈-生物圈之间的物质循环与能量交换，构建了持续演变的动态耦合系统。该过程不仅调节着深部挥发分向表生环境的传输通量，还通过氧化还原反应界面塑造极端环境微生物群落，维系地球多圈层的协同演化[1]。热液环境总体上可分为深海热液环境和陆地热液环境两大类[2-3]。其中，深海热液由海水与高温岩浆和地壳相互作用形成，其烟囱喷口主要分布于洋中脊及其扩张区域。热液喷口支撑了一个独特的生态系统，保存了生命的最早记录，并因其为前生物化学反应和古老代谢途径提供了理想条件，一度被认为是生命起源地[4-9]。陆地热液环境则通常分布于地热和火山活动较为活跃的区域，尤其常见于与地幔柱相关的地区。Djokic 等[10]在约 35 亿年前的陆地热泉沉积中发现了指示生物痕迹的结构，包括叠层石和新近发现的微生物栅栏构造，这暗示陆地热泉也可能是生命起源的重要场所。

沉积盆地中的岩浆-热液流体在各种关键矿产元素富集过程中发挥着关键作用[11]，并通过有机-无机相互作用的方式，深刻影响了沉积盆地内油气形成和聚集的全过程[12]。岩浆流体是火山弧热液矿床成矿物质的重要来源，其成矿组分(金属元素及其配位体)通过俯冲洋壳熔融和岩浆分异等多种机制在岩浆房中富集[13]。其成矿过程可能包括地壳中岩浆熔体的侵位、熔体的结晶分异演化、含水流体的出溶、流体与围岩的相互作用，以及可能的外部大气降水混入作用[11]。

热液流体中的有机分子可通过络合作用有效稳定金属元素，显著提升微量金属向全球海洋的输送通量：金属-有机络合作用可使热液系统的铁、铜输出通量分别提升至深海溶解态铁、铜总量的 9% 与 14%[14]。某些类型的矿床沉积也伴随着有机化合物的转化，金属-有机复合物可能参与增强矿床形成及其他地壳流体中金属的运输[15]。热液流体携带的能量和物质[如碳(C)、氢(H)和过渡金属元素等]促进烃源岩早熟和再活化加氢生烃，高温超临界流体可以蚀变[16]和萃取深层滞留原油[17-18]。火成岩侵入体及其伴生热液活动的热效应可以显著促进烃源岩成熟，其中幔源岩浆或超基性岩-水反应释放的活性氢可能对含油气盆地(如塔里木盆地和四川盆地等)生烃过程具有重要催化作用[19-20]。值得一提的是，Chen 等[21]认为二叠纪峨眉山大火成岩省活动导致了四川盆地古油藏和沥青的裂解，生成了大量的温室气体并产生强烈的温室效应。

本研究主要通过回顾典型场所(如深海热液喷口和沉积盆地)的热液烃实例，总结热液烃的分子地球化学特征及其形成机制，并揭示其对沉积盆地油气成藏的指示意义。此外，对于商业油气藏而言，硫酸盐热化学还原反应(TSR)、气洗、水洗、生物降解和运移分馏等已是备受关注的次生改造机制，但商业油气藏是否还存在一种新的次生机制——岩浆-热液改造？因此，通过梳理、分析全球范围内典型热液区的分子地球化学特征，可以明确岩浆-热液流体对烃类的形成、运移和聚集的改造机制，从而更好地指导全球油气资源(尤其是深层-超深层)勘探开发。

1　热液烃定义

不同类型的热液环境分布在全球不同地点，包括大洋中脊、大陆裂谷系统、造山带前和俯冲带、弧后

和火山活跃区等(图1)[2, 22-23]。张景廉[24]认为热液烃(hydrothermal hydrocarbon)是在热液条件下包括非生物成因、有机-无机相互作用生成的烃类。Rushdi和Simoneit[25]定义热液石油(hydrothermal petroleum)为有机物与热液接触后发生变化的产物。与传统石油相比,热液石油由更大温度范围(100 ~ 400 ℃)内产生的化合物组成,可由未经过成岩作用的生物前体生成。Keith和Swan[26]在AAPG大会上提出,油气可能通过白云质碳酸盐岩、富含金属的黑色页岩和其他热液蚀变矿物在冷却、分馏和沉积过程中发生的化学反应生成,从而形成甲烷及分子量更高的烃类,即热液石油。Simoneit[27]进一步完善了热液石油的概念,定义其为在高水流系统(高水/岩比)中,由沉积物中通常未成熟的有机物经快速热改变所生成的气体或沥青。尤继元等[28]提出,热液石油的有机质来源包括陆源高等植物和洋底低等生物,它们在"瞬时"(约几千年)热解过程中部分转化为烃类。

传统油气生成与盆地沉降、沉积物埋藏和有机质的逐渐成熟有关,时间跨度达数百万年[29-32]。相比之下,在深海热液喷口和陆地温泉中,烃类生成、排出和迁移的化学过程在很大程度上被压缩在一个"瞬时"的地质时间框架内[27, 33]。基于碳14同位素(^{14}C)测年数据,Guaymas盆地北部海槽、Escanaba海槽、Middle Valley和Lake Tanganyika的烃类形成所需时间分别约为7 400,17 000,29 000和25 000 a[34]。同样,沉积盆地内的岩浆活动也可加速沉积有机质热演化,从而生成热液烃[35-37]。

本文提出,热液烃(hydrothermal hydrocarbons)指在岩浆-热液活动作用下生成或接受改造的烃类,具体可划分为热液形成烃(hydrothermally generated hydrocarbons)和热液改造烃(hydrothermally altered hydrocarbons)两大类(图2)。热液形成烃可进一步分为无机形成烃和有机质经热催熟形成的烃类。无机烃的主要形成途径包括费托合成和碳酸盐矿物还原等,产物以甲烷等短链烃为主。热催熟则主要指热液作用下的快速催化过程,也包括热液流体中丰富的过渡金属元素的催化,形成的烃类通常呈现"未成熟-低成熟"特征,并具有偶碳数优势。

热液改造烃主要包括热液蚀变和热液萃取两个过程。热液蚀变是指热液流体的输入直接与原油各组分发生快速热反应,反应产物形成沥青质等重质组分,同时大量轻质组分被排出,从而形成中-重质油藏。热

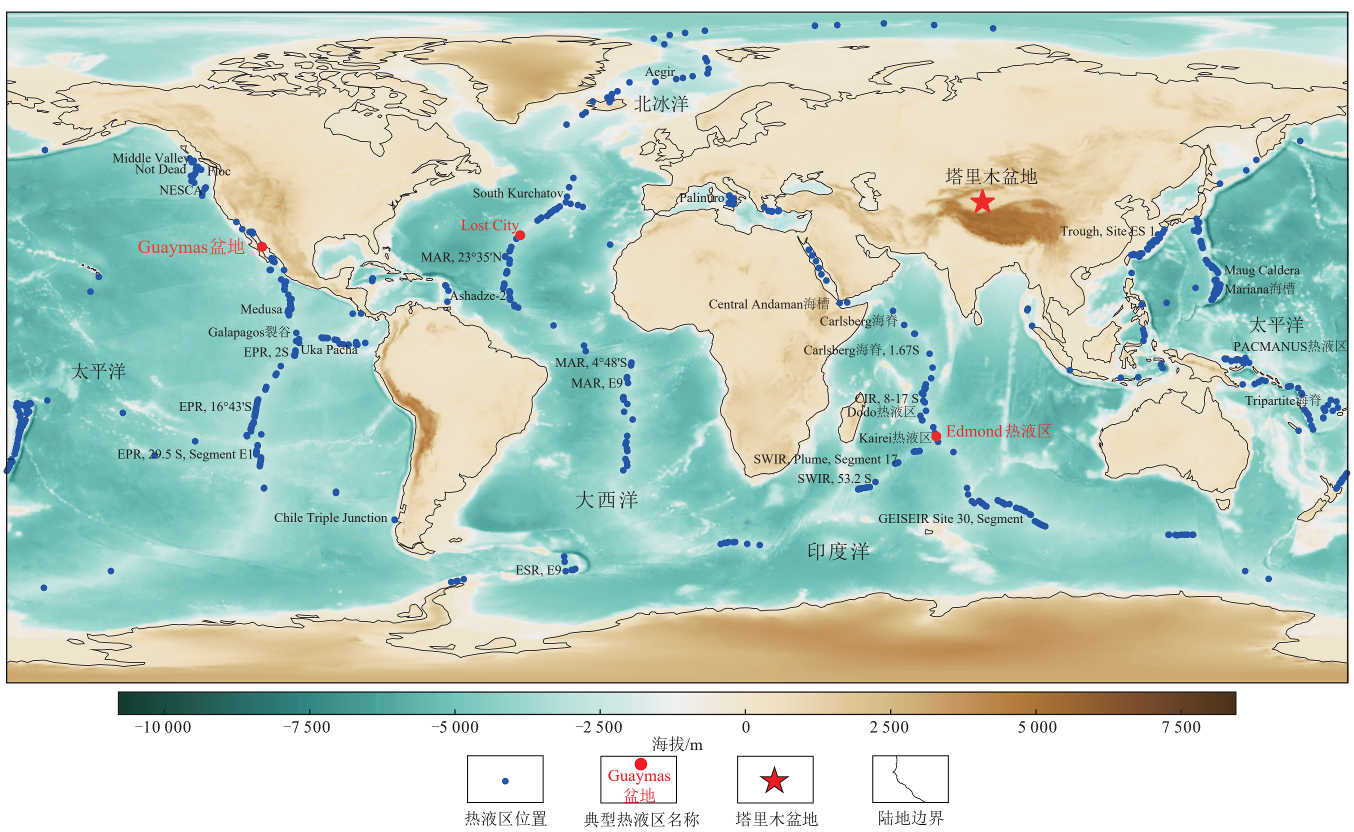

图1 全球深海热液喷口分布

Fig. 1 Distribution of global deep-sea hydrothermal vent fields

(数据来源于文献[23]。)

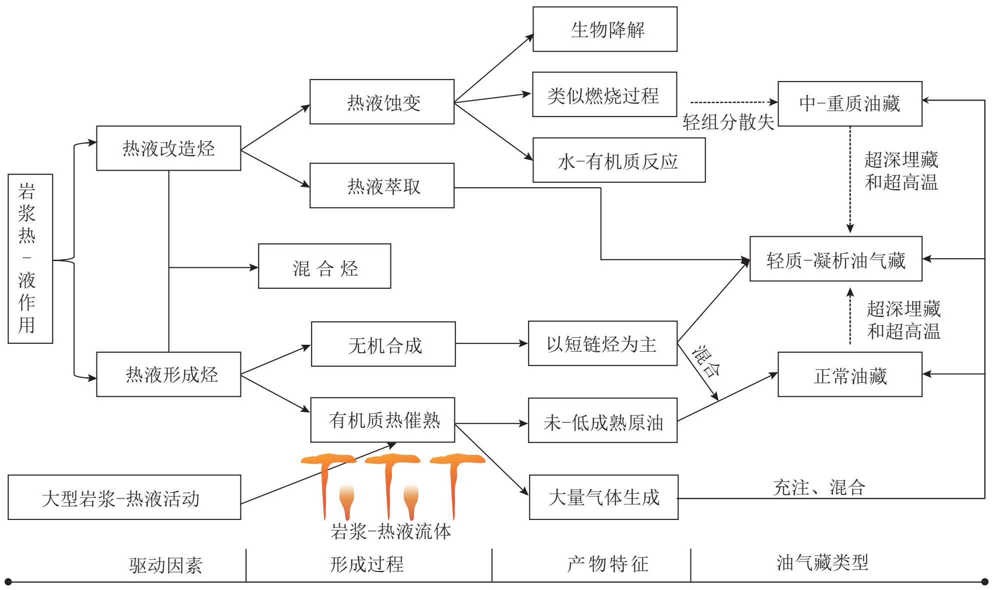

图 2　热液烃相关概念及典型地化特征

Fig. 2　Conceptual overview and diagnostic geochemical signatures of hydrothermal hydrocarbons

（图中虚线表示具有不确定性。）

液萃取是指热液流体通过萃取原始油气藏的轻质组分，形成轻质-凝析油气藏的过程。此外，产物的地球化学特征往往表现为生物降解、高成熟和有机-无机矿物相互作用的叠加。

当然，规模更大、能量输出更强的岩浆活动对油气资源形成也具有极为重要的作用。在区域型岩浆流体的烘烤下，除了岩浆释气外，富有机质烃源岩的快速加热与裂解会产生大量甲烷（CH_4）等天然气体。这些气体可再次运移至沉积盆地各个位置的油气藏中，并对原始油气藏的相态分布产生影响（图 2）。

2　热液烃分子地球化学特征

2.1　深海热液环境

热液流体中除甲烷和轻烃[38]，还富集低分子羧酸、氨基酸、水溶性维生素、有机硫化合物和部分高分子量有机物。热液沉积物中可检测到正构与支链烷烃、萜类、多环芳烃（PAHs）和脂肪酸（FAs）[25, 39-45]，丰度通常为普通大洋沉积物的数倍[46]，其中脂肪烃最为常见[47]。在多个典型热液系统中，沉积物总有机碳含量（*TOC*）与总烃含量呈显著正相关关系。例如，Guaymas 盆地上覆沉积物的 *TOC* 为 2.0%，总烃含量可达 1 000 ~ 550 000 μg/g[27]；Escanaba 海槽热液区上覆沉积物的 *TOC* 介于 0.4% ~ 5.6%，总烃含量介于 500 ~ 55 000 μg/g[48]；而在红海北部的 Shaban 深渊热液区，沉积物的 *TOC* 介于 0.6% ~ 1.5%，总烃含量仅为 240 ~ 2 700 μg/g[45]。

热液烃通常保留了生物降解的指纹信息。例如，日本 Wakamiko 破火山口海底沉积物的部分样品中正构烷烃含量偏低，且脂肪族组分色谱图中呈现显著的未分离复杂混合物（UCM），反映出中等强度的生物降解特征[49]。类似地，Guaymas 盆地热液石油样品、Rainbow 热液区烟囱硫化物样品、Lost City 热液区蛇纹石化橄榄岩样品提取物和俄罗斯勘察加半岛中部火山区 Uzon 破火山口的热液石油样品中，均可见高丰度的 UCM（图 3）。

生物降解原油中，UCM 的形成机制通常归因于微生物对链烷烃的降解作用。该过程会富集原油中普遍存在的难降解组分[52-55]，可通过正构烷烃和支链烷烃含量极低或完全缺失的特征进行识别[56-57]。热液作用形成的 UCM 则是干酪根、环烷烃和生物标志物等有机质/化合物，经历不同程度的氧化、还原、烷基化、脱烷基化、开环和脱氢环化等多重反应后的综合产物[58-59]。此类 UCM 通常呈单峰分布的低—高分子量正构烷烃序列，并具有明显的碳数优势[60-61]。二维气相色谱分析显示，热液 UCM 以构型异构体为主，芳香性随分子量升高而增强，部分样品富含含硫化合物[58-59]。

若生物降解油与热液成因油共存，则可能是由生物降解油和后期迁入烷烃油混合形成。若正构烷烃同系物具有显著碳数优势，且同时伴随明显的 UCM，通常指示石油处于热蚀变或生物降解的中间阶段[59]。此外，UCM 与可分辨峰的相对丰度亦可作为热液改造

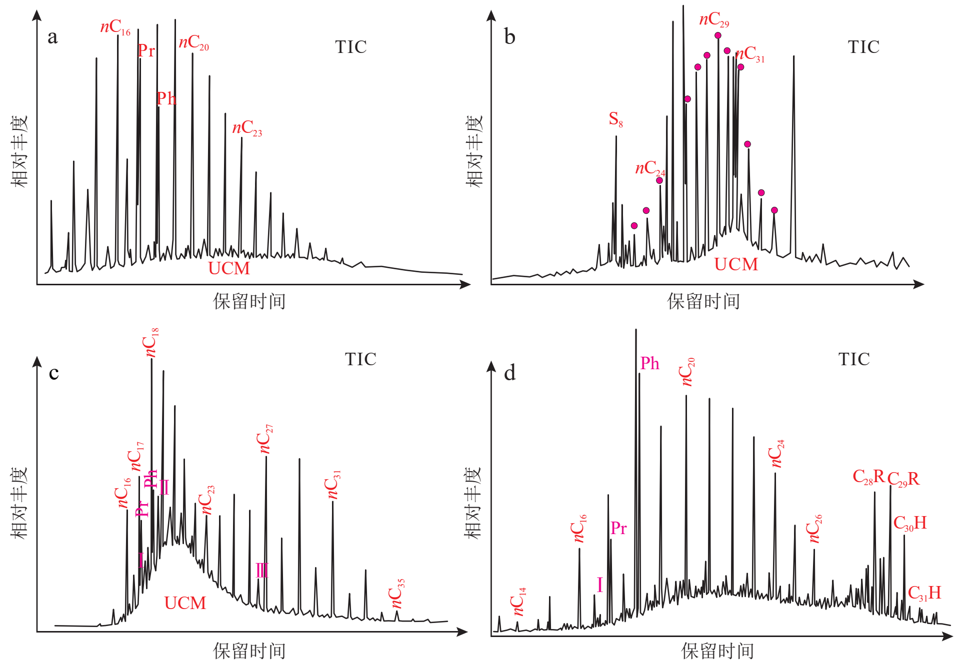

图3　典型热液区样品正构烷烃和异戊二烯烃分布特征气相色谱

Fig. 3　Distributions of *n*-alkanes and isoprenoids in samples from representative hydrothermal areas

a. Guaymas盆地热液石油样品[61]；b. Rainbow热液区烟囱硫化物样品[40]；c. Lost City热液区蛇纹石化橄榄岩样品提取物[50]；d. 俄罗斯Kamchatka半岛中部火山区Uzon Caldera热液石油样品[51]

nC_{16}—nC_{31}. 碳原子数16—31的正构烷烃；S_8. 八元环硫；UCM. 未溶复杂化合物；Pr. 姥鲛烷；Ph. 植烷；C_{28}R. C_{28}规则甾烷；C_{30}H. C_{30}藿烷；C_{31}H. C_{31}藿烷；Ⅰ. 降植烷(Norpristane)；Ⅱ. 正十八烯(*n*-Alcene C_{18})；Ⅲ. 角鲨烷(Squalane)；TIC. 总离子流图

强度的重要标志[62]。值得一提的是，在Middle Valley热液系统中，烃类的初次运移与二次运移均为快速过程，而生物对分子化合物的改造通常需要更长的时间，因此在该系统中，生物降解对分子标志物的影响应当予以排除[25]。

热液系统的生物标志物特征反映母质来源和成因环境。Wakamiko沉积物中，姥鲛烷(Pr)和植烷(Ph)的丰度高于正十七烷(nC_{17})和正十八烷(nC_{18})，表明存在陆源高等植物碎屑的输入；PAHs中菲/甲基菲含量比值偏低，指示高成熟成因，而未成熟藿烯与苝的共存则揭示部分有机质来自未受热蚀变的原始沉积物[49]。Escanaba海槽沉积物整体表现为"低丰度、高演化"特征，沥青质以缩合PAHs为主[63]。位于印度洋Andaman Backarc盆地的热液沉积物中，生物成因的正脂肪酸、偶碳优势的正醇及藿烷和藿烯系列的存在，指示了新生有机质的贡献；而高分子量、具奇碳数优势的正构烷烃及具偶碳数优势的正烷醇则反映了陆源高等植物的输入[64]。

Guaymas盆地热液石油在分子组成方面具有代表性。正构烷烃碳数分布范围主要在C_{12}—C_{30}，且无明显碳数优势(图3a)[65]，富含类异戊二烯烃、成熟生物标志物(如α-藿烷)和氧化及硫代多环芳烃[27]。通过二维气相色谱-质谱技术，共鉴定出5 800余种有机化合物，涵盖正构和支链烷烃、PAHs及苯并噻吩类至六环结构的复杂芳烃[66]。Rainbow热液区硫化物样品中的可萃取有机质包括高分子烷烃(图3b)、PAHs和脂肪酸。其中，支链烷烃含有偕二乙基烷烃系列(源于硫氧化细菌)和古菌标志物双植烷[40]。Lost City蛇纹石化橄榄岩样品中，正十六烷(nC_{16})—正三十五烷(nC_{35})分布(图3c)及长链组分(至C_{40})与Pr、Ph、藿烷和甾烷的存在，共同指示海相有机质的贡献[50]。

热液烃的碳同位素组成可进一步揭示其混合成因。热液沉积物与大洋沉积物中正构烷烃的稳定碳同位素比值($\delta^{13}C$)范围为-31.3‰～-25.3‰，显示陆源与海洋有机质的混合特征[67]。其中，低分子量正构烷烃的$\delta^{13}C$高于大洋沉积物样品，说明陆源贡献较低[68-70]。随碳原子数量的增加，热液沉积物样本中正构烷烃的$\delta^{13}C$略有下降，这种分布趋势可能指示了无机成因正构烷烃的存在[69]。类似的碳同位素分布趋势也见于其他典型热液区，比如Okinawa海槽[43]，Escanaba海槽[71]，中印度洋脊和大西洋中脊[72]和Middle Valley[67](图4)。

综上所述，深海热液系统中的有机分子表现出多源混合与微生物协同改造的特征。热液流体不仅促进

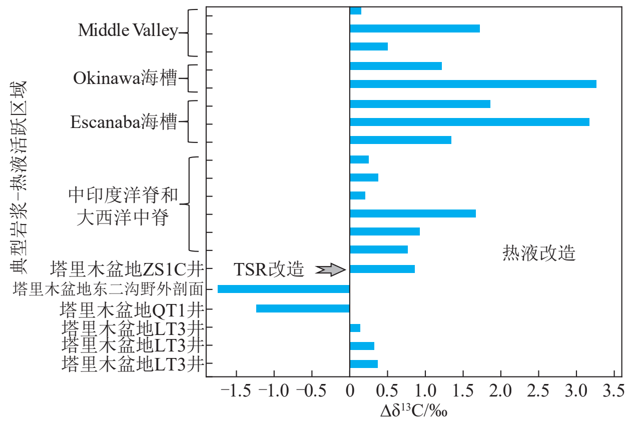

图4　典型热液区与塔里木盆地烃类的低碳数正构烷烃(C_{21-})与高碳数正构烷烃(C_{22+})碳同位素差值($\Delta\delta^{13}C=\Sigma\delta^{13}C_{21-}-\Sigma\delta^{13}C_{22+}$)对比

Fig. 4　Carbon isotopic differences between low-carbon-number ($\leqslant C_{21}$) and high-carbon-number ($\geqslant C_{22+}$) *n*-alkanes in hydrocarbons from representative hydrothermal areas and the Tarim Basin

(中印度洋脊和大西洋中脊,Escanaba海槽,Okinawa海槽和Middle Valley热液区数据分别收集于文献[72],[71],[43]和[67]。)

(图中灰色箭头表示ZS1C井可能接受了TSR改造。)

了有机质的热改造与结构重组,也显著提高了体系分子复杂度。

2.2　陆地热液环境

陆地环境中,岩浆侵入与热液活动对有机质热演化具有显著影响。受接触变质作用控制,镜质体反射率(R_o)和沥青反射率(BR_o)均表现出随靠近岩浆体而升高的趋势[73-78]。例如,Li等[79]报道在距岩墙50 m处的R_o为2.6%,而在靠近接触带区域,该值升高至3.7%。Goodarzi等[80]在加拿大北极区的两个钻孔中发现,BR_o由热晕边界的1.5%急剧升至约7.0%,其变化幅度远超R_o,表明BR_o对热影响强度的记录更为灵敏。在多个陆相盆地中(如巴西巴拉那盆地下二叠统Irati组、瑞典中南部寒武系—奥陶系Alum Shale组和美国拉顿盆地白垩系Vermejo组),成熟度参数[如甲基菲指数(MPI-1)]在朝侵入体方向上呈系统变化,通常在中等距离处上升最为明显,而在靠近接触带时因热扰动剧烈而分布紊乱[81-83]。

岩浆-热液活动同样对分子化合物转化有显著影响。煤系沉积物随距岩墙的距离减小,其4～6环PAHs含量下降,2～3环组分相对富集,烷基化芳烃整体减少,表明高环芳烃在高温条件下易断裂或发生环化降解[84]。靠近侵入体的页岩样品中,烃类浓度明显降低,伴随元素硫富集和Pr优势现象[85]。沥青质则显示出倍半萜、二萜、三萜和甾烷等高成熟化合物与低烷基PAHs和含硫、氧杂环芳烃共存的双峰分布特征,反映了生物降解与热解的叠加效应。受热样品中干酪根芳香化显著增强,并富集^{13}C,^{34}S和^{2}H同位素。勘察加半岛Uzon破火山口的热液油样富含正构烷烃(图3d)、甾烷和藿烷等生物标志物,^{14}C同位素年龄显示距今约为1 000 a,说明热液石油组成包括了低温缓慢生成的正构烷烃和快速生成的UCM[51]。

在滇西北兰坪盆地金顶铅(Pb)-锌(Zn)矿床中,有机质与硫化锌(ZnS)和硫化铅(PbS)共存,后者可催化多环化合物的脱氢环化并形成含苯基和含硫杂环中间体,反映了热液氧化还原条件[86]。类似地,Zn-Pb矿床中三苯并[1,12-bcd]呋喃/9-苯基菲含量比值被认为是热液反应强度的分子指示[58]。Schito等[87]报道了意大利南部Tuscany地区基底变质岩里的热液烃特征:大多数饱和烃类生物标志物消失,但保存了大量燃烧衍生的PAHs(如荧蒽、芘、菊烯、苯并[b]荧蒽、苯并[e]芘和苯并[a]蒽),还包括高丰度的5环和6环燃烧源PAHs(如茚并[1,2,3-cd]芘、二苯并[a,h]蒽和苯并[ghi]苝)。在塔里木盆地塔中18井志留系受辉绿岩侵入的砂岩储层中,BR_o高达3.5%,原油密度大、碳同位素偏重($\delta^{13}C$介于-29.26‰～-27.18‰),C_{14}—C_{20}烃类含量升高且具偶碳优势,未烷基化芳烃(如菲、芘和苯并[a]蒽)相对丰富[88]。顺北地区原油随热液作用增强,菲环体系氧化生成二苯并噻吩,并通过联苯环引入硫元素[16];高温侵入还可诱导高分子量(≥5环)和燃烧成因PAHs的显著富集[89]。

2.3　热液烃判识指标

热液烃分子组成本质上受到有机-无机相互作用的控制[90-92]。热液模拟实验表明,当温度介于250～300 ℃时,可萃取有机质以极性组分为主(含量>70%),包含正构烷酸、烷二酸、烷醇和类异戊二烯酮等,并伴生支链及环状化合物形成的UCM。当温度超过300 ℃后,产物以正构烷烃、生物标志物和UCM为主(三者一共占总产率的95%以上)[93]。在热液蚀变过程中,脂肪烃类生物标志物发生了不可逆的降解[2,62],高分子量生物标志物丰度降低,甾烷图谱常出现UCM鼓包[2]。典型的分子地球化学特征还包括饱/芳比升高,UCMs丰度增加,正构烷烃分布呈弱偶碳数优势,碳优势指数(CPI)降低,链状苯基化合物(如联苯)与含硫化合物(如噻吩类)含量相对增加,以及Pr/nC_{17}与Ph/nC_{18}含量比值增大[25,88,93-94]。轻烃中,甲苯可经氧化脱羧生成苯[95],但Main Endeavour热液区甲苯与苯未达平衡[96]。傅里叶变换离子回旋共振质谱

(FT-ICR-MS)结果显示,大西洋中脊溶解有机质分子量、氧(O)/碳(C)含量比和双键当量均较低,而芳香性显著增强[97]。Simoneit[27]在Guaymas盆地研究中,总结了深海热液石油与常规储层石油之间的主要相似性和差异(表1)。值得注意的是,高硫含量可能是热液石油的诊断性特征,这一点与常规油气藏明显不同。此外,高浓度的母体多环芳烃和显著的杂环分子化合物,也可能指示热液烃的存在[2, 27]。

塔里木盆地原油中,热液蚀变促使多氢化菲芳构化增强,从而导致PAHs富集[16, 89]。菲与蒽一旦形成便具有较高热稳定性,但在特定条件下,菲可发生甲基化生成甲基菲[98-99]。根据Saha等[100]建立的端元模型,甲基菲(MP)/菲(P)含量比值约为0.4与2.0,分别代表石油源与燃烧源PAHs,极端热事件可导致MP含量下降、P相对富集[101]。在Guaymas盆地和Escanaba海槽热液系统中可见到,*MPI*与P/MP比值总体呈逆相关的趋势(图5)[102-103]。*MPI*与P/MP比值的反向耦合可能反映芳构化与烷基化竞争。样品的数据点分布区域几乎介于两条平行线之间,因此推测该区域可能为典型的热液改造区域。类似地,塔里木盆地LT3井和ZS1井样品的数据点刚好位于典型区域内。此外,LT3井的一个样品表现出极高的*MPI*,而该样品深度相对低于其他两个样品(图5),据此推测P/MP比值越高可能指示更强烈的热液活动。由于MP含量的增加指示燃烧源的强度降低,因此热液系统中的菲系列化合物转化是正常热成熟演化和燃烧过程的叠加。

表1 热液石油与常规石油差异对比(修改自文献[27])

Table 1 Contrasting characteristics of hydrothermal and conventional petroleum (modified after reference [27])

相似性	含天然气和轻烃(碳数为C_1—C_8)
	含完整碳数烃类,无奇偶优势
	含环烷烃(主要是支链和环链烃类的不溶复杂混合物)
	显著的异戊二烯烃含量
	可见一定丰度的生物标志物
	含CO_2、H_2S、苯和甲苯等
	含烷基芳烃和沥青质
不同性	热液石油含高浓度母体PAHs
	热液石油含残留的未成熟生物标志物和中间体(如17*β*(H)-藿烷、藿烯、甾烯)
	热液石油不同程度降解的生物标志物(主要含C_6—C_{20}的柴油烃,最高到C_{27}的卟啉)
	热液石油显著的杂环芳烃化合物(含N和S)
	热液石油高S含量
	热液石油沥青中的烯烃含量与源沉积物几乎一致
	热液石油含烷酮和烷基酚

注:CO_2. 二氧化碳;H_2S. 硫化氢;N. 氮;S. 硫。

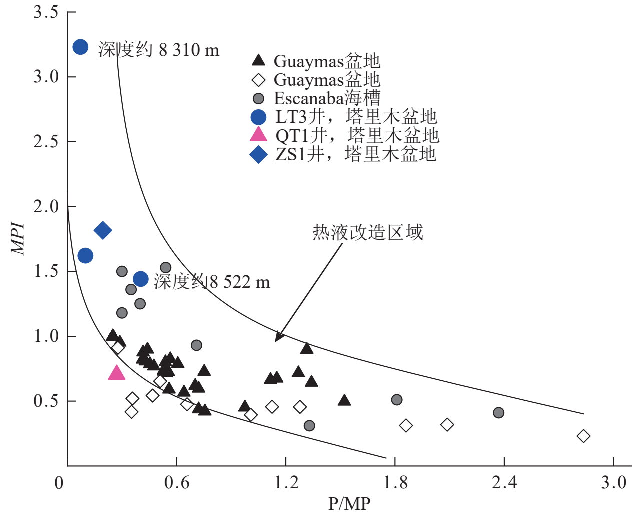

图5 典型热液区及塔里木盆地烃类的*MPI*指标与P/MP指标交会图

Fig. 5 Cross plot of methylphenanthrene index (*MPI*) vs. phenanthrene-to-methylphenanthrene ratio (P/MP) for hydrocarbons from representative hydrothermal areas and the Tarim Basin

MPI. 甲基菲指数;P/MP. 菲/甲基菲含量比值

(所有样品均为塔里木盆地下寒武统泥页岩钻井岩心;ZS1井可能接受了TSR改造(据参考文献[104]);空心菱形数据收集自文献[102],黑色三角形数据收集自文献[103],Escanaba海槽数据收集自文献[63]。)

正构烷烃单体碳同位素对热液有潜在的指示意义。本次研究计算了低碳数与高碳数正构烷烃单体稳定碳同位素的差值$\Delta\delta^{13}C$($\Delta\delta^{13}C = \Sigma\delta^{13}C_{21-}-\Sigma\delta^{13}C_{22+}$)。结果显示,该比值在典型的热液系统中存在高度相似性,均大于0(图5)。比如,Middle Valley,Okinawa海槽,Escanaba海槽和中印度洋脊和大西洋中脊样品中的$\Delta\delta^{13}C$分布范围分别为0~1.6,1.0~3.5,1.2~3.5和0~1.7。而在本次收集的塔里木盆地样品中,LT3井样品的$\Delta\delta^{13}C$均大于0,呈现出典型的热液改造特征。此外,中深1井的样品已被广泛认为是接受了TSR改造,其$\Delta\delta^{13}C$同样大于0。其余样品(如QT1井和东二沟剖面野外露头样品)$\Delta\delta^{13}C$均小于0,说明未接受或者接受了微弱的热液改造(图5)。

塔里木盆地的生物标志物成熟度参数异常也可能指示岩浆-热液影响。比如,LT3井深度大于8 000 m的样品显示为低甾烷异构化参数,而奥陶系烃源岩的成熟度参数甚至高于寒武系烃源岩等[104]。深部流体携带的能量可驱动烃源岩早期成熟,并通过活化加氢作用有效促进高成熟烃源岩的生烃过程[12]。催化加氢实验可在一定程度上类比热液活化烃源岩生烃的过程。催化加氢模拟实验表明,常规成熟度参数在此类过程中会呈现异常低值特征[105]。加氢热解技术释放

的键合态生物标志物,不仅具有低成熟地球化学特征,更保留了原始母质信息[106]。在塔里木盆地烃源岩干酪根催化加氢实验中,热解产物中的低碳数正构烷烃(nC_{14}—nC_{20})具有明显的偶碳优势,部分样品nC_{22}优势明显[107]。对于塔里木盆地广泛报道的偶碳数正构烷烃优势,Huang等[108]认为可能是岩浆-热液影响所致,这与前述典型热液区的分子地球化学特征类似。

3　热液烃形成机制

地质体系中的有机化合物主要通过3类机制形成:① 生物成因,即由微生物代谢活动直接形成,或由生物残体经成岩和热解转化生成;② 热成因,即有机质在升温过程中经历的热裂解与重组;③ 非生物成因,即在无生物参与下由无机反应生成的产物[68, 109]。例如,甲烷和醋酸等低分子有机物,它们既可源于生物代谢,也可通过热解或费托合成(FTT)等无机途径生成[40, 72, 110-113]。本文将微生物作用下形成的烃类和有机质热成因形成的烃类统一归为生物成因。陆地热液系统因受光合微生物输入影响,其有机质中常富含光合作用标志分子;而深海系统主要体现化能合成特征[3, 114-115]。

3.1　生物成因

热液体系中的生物成因烃表现为多源混合与多阶段转化特征,其生成与保存受微生物群落代谢、温度和氧化还原条件共同控制。深海热液系统中缺乏阳光,主要依赖化能合成。微生物利用硫化物、氢气(H_2)、甲烷(CH_4)和亚铁离子(Fe^{2+})等还原性物质氧化反应获取能量,经碳固定形成有机质[116-118]。这些微生物包括与动物共生的内共生体、微生物席以及自由生活的细菌与古菌。群落结构受温度和pH控制:温度升高通常导致多样性下降但古菌比例增加,中性-弱碱性环境最有利于多样性维持[119]。例如,碱性氯化物型热液硅华沉积体系的空间分异性呈现典型梯度:高温区(温度>73 ℃)以化能营养型古菌与细菌为主;中-远部过渡带光合细菌占据优势;远端边缘及沼泽湿地则发育真核生物群落(含硅藻等)[120]。

硫酸盐还原菌(SRB)在热液体系的烃类生成与转化中扮演重要角色。其代谢产物硫化氢(H_2S)与中间有机物可参与饱和及不饱和烃的转化[121-122]。在印度洋表层沉积物中,Adam等[123]发现绿弯菌门(*Chloroflexi*)、α-变形菌纲(*Alphaproteobacteria*)、β-变形菌目(*Betaproteobacteriales*)、硝化螺旋菌目(*Nitrospirales*)、芽孢杆菌目(*Bacillales*)、浮霉菌门(*Planctomycetes*)和*Nitrosopumilus*属等微生物类群占据优势,其相应的代谢过程将会影响热液烃的组成与分布。同样,中印度洋脊与大西洋中脊热液区的短链烷烃(nC_{16}和nC_{18})也与硫代谢微生物活动相关[50, 72]。嗜热硫酸盐还原古菌*Archaeoglobus fulgidus*具备饱和烃氧化能力,暗示热液喷口及深部生物圈存在高温烃类氧化过程[124]。SAR324,SUP05及*Thiobacillus*属的硫氧化菌能降解烷烃,而红杆菌属与SAR202分支则可分解PAHs[125]。低温流体中检测到维生素及氨基酸,被认为是次表层微生物代谢产物,为喷口周围异养生物提供碳氢源[111]。

微生物死亡后,其生物残体经热解或次生改造可形成烃类。该过程在温度低于150 ℃时即可启动,首先会裂解脂质及不稳定大分子,形成轻质烃;当温度介于150~300 ℃时,以芳构化与缩合为主;当温度大于300 ℃时,逐步生成多环芳烃与杂环结构[27]。红海热液区检测到C_{40}类异戊二烯烃,指示产甲烷菌及嗜热古菌贡献[45]。Rainbow热液区硫化物样品中发现正构与支链烷烃、UCM、PAHs、萜类及脂肪酸,支链烷烃包含典型偕二乙基烷烃系列和古菌标志物双植烷,表明烃类来源于细菌与古菌生物质的热转化[40]。在中印度洋脊Kairei与大西洋Logatchev热液区,富集的类异戊二烯烃和正构烷烃以及其轻碳同位素值($\delta^{13}C$<-30‰)特征,显示光合生物输入与热液微生物共同贡献[72]。大西洋中脊热液流体和烟囱中烷酸组分的偶碳数优势特征虽然明确指示其生物成因属性,但其究竟是热液喷口附近烟囱体内部的原位微生物活动直接生成,还是深部热液系统内形成的有机组分经流体迁移至此沉积富集[33]仍未有定论。Hu等[126]认为表层海水和沉积物中的正构烷烃大多来自藻类和高等植物,也有少量来自人为和生物来源。此外,经风力、洋流或地下水输运的外源有机质对原地分子标志物分布的影响也不可忽视[3]。

3.2　非生物成因

非生物成因烃主要通过CO_2或一氧化碳(CO)的还原反应生成,其中FTT机制最具代表性。FTT过程是工业领域著名的CO_2还原过程,最初旨在将煤源CO转化为液态烃类,以获取燃料与润滑油等工业产品[127-128]。实验显示,在150~250 ℃温度条件下可生成含氧脂类与短链烃。当温度升至300~400 ℃时,反应趋于平衡,芳香化程度增加,产物以PAHs为主[129]。在温度为390 ℃、压力为40 MPa的条件下,除CH_4外,在铁和铬矿物催化作用还可生成乙烷(C_2H_6)与丙烷

(C_3H_8)等气态烃[130]。铁(Fe)-钴(Co)体系则能高效将碳酸氢盐还原成长链烷烃(≤C_{24})[131],显示天然Fe-镍(Ni)-Co硫化物及磁铁矿等矿物可在热液条件下充当有效催化剂。

野外观测亦提供了无机成因证据。Lost City热液区C_1—C_4烃类的稳定碳同位素呈逆序分布,指示FTT合成,而^{14}C同位素分析排除海水碳酸氢盐输入性[132]。Von Damm热液区甲酸(HCOOH)与CO_2浓度相当,表明甲酸盐既可为FTT产物,也可作为微生物代谢底物[133]。Simoneit等[40]提出Rainbow热液区中的CH_4和硫化物中的少量烷烃可能是非生物来源,这是由于非生物成因烃类的浓度随烷基链碳数增加呈系统性递减趋势,且不具奇偶碳数偏好性[68],并且很可能与费托合成有关[50]。超基性岩热液系统被视为无机合成的理想场所[68, 134]:当水与超基性岩中的橄榄石接触时,发生蛇纹石化作用,在此过程中亚铁离子(Fe^{2+})被氧化,同时水被还原生成H_2。该过程产生的H_2不仅可作为化能自养菌的能量来源,在高温条件下更能与CO_2结合,通过FTT反应合成烃类及脂肪酸等有机化合物,这一机制可能直接促成了Rainbow热液区C_{16}—C_{29}直链烃的生成[112, 135]。Konn等[69]亦推测Lost City与Rainbow流体提取物中的部分正构烷烃及烷酸可能具有非生物来源。然而,McCollom等[33]发现所有热液流体提取物均未显示确凿的非生物有机化合物证据。^{4}He同位素是由地壳中铀(U)和钍(Th)等放射性元素衰变产生的;而^{3}He同位素来自地幔,主要通过地幔熔融或交代流体流动释放,并通过断层、地壳流扩散和岩浆侵入等方式运移到地表,主要发生在大陆伸展或岩浆活动区域内[136]。已收集的热液喷口数据显示,氦气同位素比值(R/R_a,其中R为样品中的^{3}He/^{4}He含量比;R_a为标准大气中的^{3}He/^{4}He含量比)均大于2.5(平均值为7.9),指示典型的幔源成因(图6)。

古老地层中也可见到无机合成烃的证据。海水与广泛的富含(Fe^{2+})的火成岩矿物和碳酸盐之间的热液流体-岩石相互作用可能在生物前地球上产生了广泛的有机化合物[147-148]。太古宙硅质岩中的碳质物可能源于热液-岩石反应,如CO_2还原、含铁碳酸盐分解及蛇纹石化作用[149-150]。澳大利亚Pilbara克拉通Dresser组地层及其下伏玄武岩(地质年龄 > 3.5 Ga)的黑色燧石脉体内观察到了碳质材料,但由于这个地区缺乏富含有机质的沉积物,说明热液降解后的生物质并非迁移有机碳的主要来源,暗示了可能有非生物成因烃类的贡献[151]。此外,虽然北极地区($\delta^{13}C$介于-38.1‰ ~ -29.4‰)黑色硅质岩中碳质物质的贫^{13}C组成与生物分馏一致[152-154],但模拟实验和陨石分析表明,非生物过程也可以产生贫^{13}C[155]的还原性有机化合物。火星陨石ALH 84001中的纳米级碳质矿物同样被解释为蛇纹石化与碳化反应的产物[156],说明非生物合成在早期行星演化中具有普遍意义。

3.3 混合成因

混合成因机制或许更能解释热液系统中的复杂分

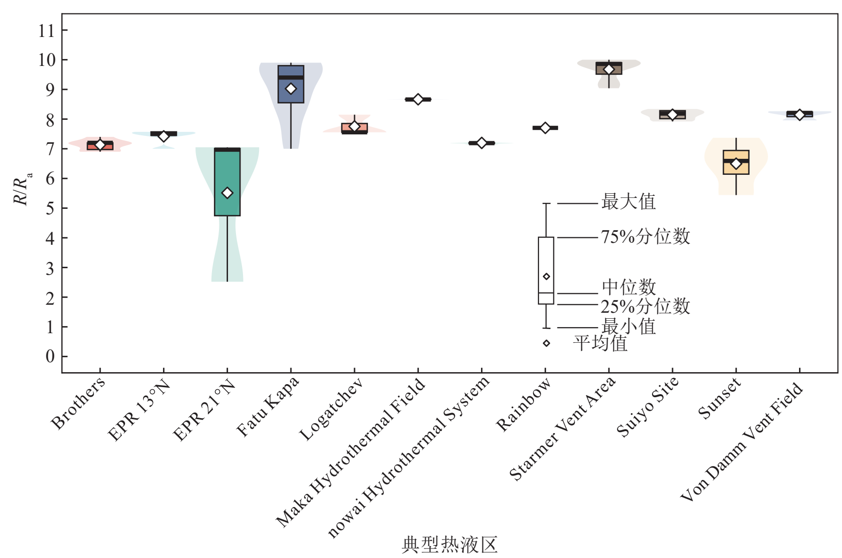

图6 典型热液喷口的氦同位素分布

Fig. 6 Helium isotope distribution of representative hydrothermal vent fields

R. 样品中的^{3}He/^{4}He含量比;R_a. 标准大气中的^{3}He/^{4}He含量比

(数据收集自文献[137-146]。)

子特征。在Milddle Valley热液区，沉积有机质的蚀变过程同时产生长链溶解态烃类和CO_2，其中CO_2既可源自含氧官能团的直接脱羧作用，亦可由溶解烃次生氧化形成[157]。*Pyrococcus abyssi*生物质热液条件下的降解实验表明，Rainbow热液区的流体中部分脂肪烃可能具有无机起源，而流体中的烷基苯、烷基萘和PAHs主要为热成因[70]。Menez Gwen热液区的脂肪酸及Rainbow热液区的PAHs可能部分源自非生物成因过程（如FTT等），而Lucky Strike和Rainbow热液区正构脂肪酸的富集则与微生物活动等生物成因机制密切相关[158]。

热液喷口流体中发现的甲烷和CO_2可能有多种来源，包括生物输入、有机质的热降解、岩浆气体的直接注入、玄武岩中捕获的岩浆气体的提取，以及热液循环过程中CO_2还原的非生物合成。稳定碳同位素和氢同位素可以用于判识CH_4和CO_2的成因[159-163]。全球典型热液区中的甲烷碳同位素值（$\delta^{13}C_{CH_4}$）介于−54.0‰～8.9‰，甲烷氢同位素值（δD_{CH_4}）介于−250.0‰～−93.0‰，CO_2碳同位素值（$\delta^{13}C_{CO_2}$）分布于−19.0‰～9.5‰，整体处于热成因和无机成因的区间（图7）。值得注意的是，热液系统中的CH_4同位素值分布于一个较广的区间，数据解释时并不能简单地将同位素偏轻归因于单一成因。轻碳同位素富集表明甲烷可能同时受非生物成因与热成因贡献；而重碳同位素富集则主要反映微生物氧化作用[164]。Okinawa海槽区域Minami-Ensei热液区中的热液端元流体$\delta^{13}C_{CH_4}$介于−26.0‰～−24.7‰（指示热成因），而烃类组成却呈现CH_4绝对优势特征（指示典型生物成因）[165]。

4　成藏启示

4.1　热液蚀变油气藏

热液流体的蚀变作用是导致油气相态差异分布的重要机制。在微观机理上，常规热成熟过程以均裂反应为主，倾向于生成非环状烃[93, 178]；而热液蚀变则以异裂反应为主，反应产生的配对电子离子易与水或矿物发生相互作用，改变反应路径与活化能，从而促进分支烃和环状化合物的生成[179-180]。这种特殊的化学动力学过程在宏观上表现为显著的相态改造效应。

实例分析表明，不同地质背景下的热液蚀变产物呈现出极大的差异性。在塔里木盆地塔中18井，受火成岩侵入产生的异常高热应力影响，志留系砂岩储层原油密度显著增大，甚至演变为黑色碳质沥青[88]；Guaymas盆地亦表现出类似的热液稠油特征。相反，顺北地区则展示了热液活动与轻质化的耦合关系：从顺北7号断裂带经5号断裂带至1号断裂带，随着断裂带热液活动强度的变化，油气藏类型由黑油油藏向轻质油及凝析气藏有序过渡[16]；苏北盆地黄桥地区也呈现出热液成因的轻质油/凝析油特征。

上述现象表明，热液对油气相态的改造并非单一

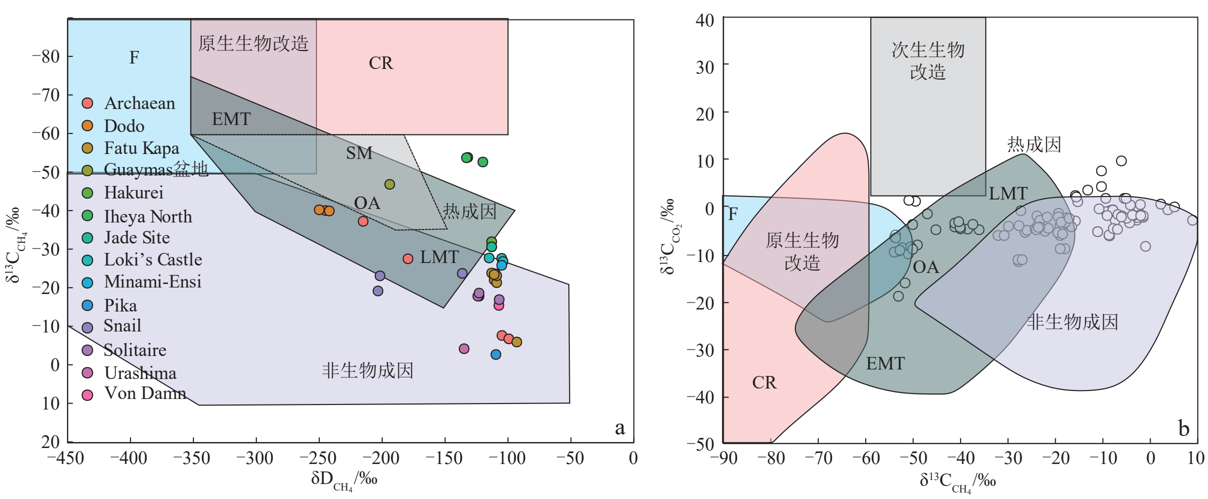

图7　典型热液喷口的CH_4碳、氢同位素组成及CO_2碳同位素组成分布

Fig. 7　Distributions of the carbon and hydrogen isotopic compositions of CH_4 and the carbon isotopic composition of CO_2 in representative hydrothermal vent fields

a. 典型热液喷口CH_4的碳、氢同位素组成；b. 深海热液区CO_2和CH_4的碳同位素组成

CR. 二氧化碳还原；F. 甲基型发酵；SM. 次生生物甲烷气；EMT. 低演化热成因气；OA. 原油伴生热成因气；LMT. 高演化热成因气；δDC_{CH_4}. 甲烷氢同位素值；$\delta^{13}C_{CH_4}$. 甲烷碳同位素值；$\delta^{13}C_{CO_2}$. 二氧化碳碳同位素值

（图版引自文献[163]，数据收集自文献[137, 138, 141, 142, 158, 166-177]。）

的线性过程。热液流体既可导致原油裂解生烃(轻质化),也可因高温氧化或散失导致稠化(沥青化)。因此,在解析热液控藏效应时,必须摒弃单一因素思维,将热液活动强度与原始油气性质、断裂输导效能及盖层保存条件等关键成藏要素进行时-空耦合分析,方能准确揭示现今油气相态的成因机理。

4.2 热液萃取与迁移机制

即使在微小空间尺度内,热液喷口区含油气沉积物的有机组成仍呈现高度异质性特征[66]。热液系统中不同热解机制与动态变化的温度梯度、运移速率共同作用,可能因多组分流体的差异气溶效应和水动力改造而导致成分分馏效应。与常规储层石油不同,多数热液石油含有显著比例的极性组分,推测源于极性未成熟组分的溶解或平流作用。在Guaymas盆地,差异冷凝/固化、生物降解与水洗作用共同造成烃类组分的选择性流失[181]。Escanaba海槽热液区的低分子量PAHs因热液流体优先迁移,残留组分以高分子量PAHs为主[63]。相较而言,藿烷、甾烷和双植烷脂类等饱和烃生物标志物迁移能力较弱,在向海底运移前更易发生裂解或芳构化作用[59]。此外,深部地堑构造及邻近断裂带的样品相较于地形高部位呈现更显著的热液石油富集[64]。

热液流体的萃取作用导致不同碳数的烃类差异聚集。液态CO_2对有机化合物具有优异溶解性能,因此热液系统近临界域(温度为300~400 °C,压力为20~30 MPa)中,伴随CO_2等共溶质的存在,不仅能够显著提升烃源岩内有机质(如石油)的反应速率,还可通过“共溶剂效应”增强其溶解-迁移能力,比如Guaymas热液系统中的烃类随热液流体逸散至海水中[27](图8)。Monin[182]发现,超临界CO_2萃取的nC_{30}—nC_{35}烃类的百分比相对低于氯仿萃取,而碳数小于C_{30}的烃类所占百分比相对后者较高。Bondar和Koel[183]报道了乌克兰Boltysh油页岩的超临界CO_2萃取情况,萃取得到的小分子质量烷烃组分(nC_{20})的浓度相对高于传统索氏提取得到的饱和烃。在中国东部和世界其他地区的含油气盆地中,发现了大规模的幔源CO_2萃取以及CO_2和原油的共同聚集现象。苏北盆地黄桥地区油藏的许多油井可见大量CO_2,原油为轻质油或凝析油(密度为0.79~0.82 g/cm^3),饱和烃占比90.06%~97.37%,芳烃、非烃类和沥青质馏分很少,主峰碳为nC_{16}和nC_{17}[17]。这些特征综合表明深层超临界CO_2在沿深部断层、裂缝向上运动或流经源岩的过程中,自然地从源岩中提取了碳氢化合物,特别是小分子碳氢化合物,然后将其带到浅层,形成了CO_2石油耦合成藏[18]。同样地,东海盆地丽水凹陷中也观察到富CO_2流体对烃类的提取和驱替,并促成烃类的再成藏[184]。

4.3 岩浆-热液作用下的资源量增加

在沉积盆地中,岩床侵入体周缘热晕内富有机质沉积物通过接触变质作用可形成大量CH_4和CO_2等温室气体[186]。单层岩床周缘热晕内挥发分的生成时间尺度为10~1 000 a。在总有机碳含量大于5%的页岩中,有机质裂解生成的CH_4(含量为85~135 kg/m^3)是主要挥发组分,其生成量显著高于脱水反应产生的水(含量为30~110 kg/m^3)[187]。单个薄层岩床(约15 m厚)在超过1 000 km^{2}范围内,具备生成数亿吨CH_4气体的潜力[186]。例如,挪威Vøring盆地和Møre盆地的侵入

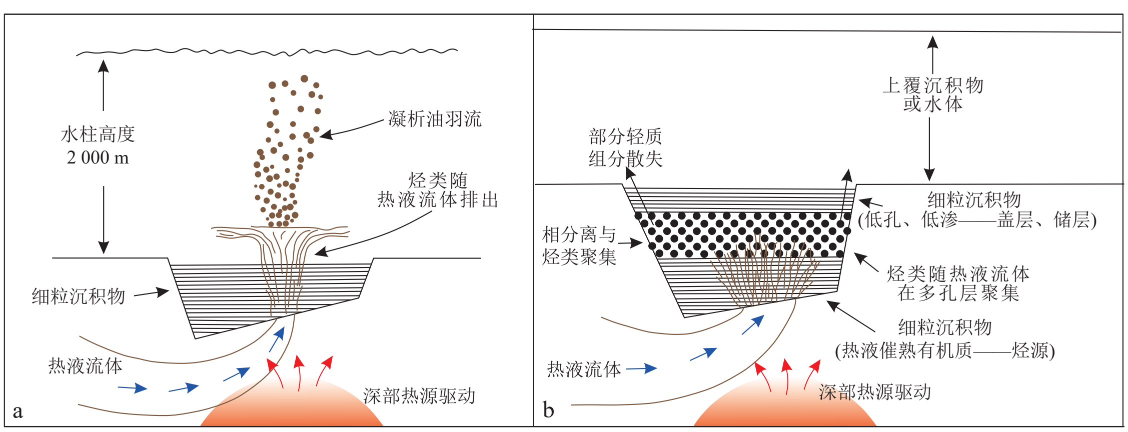

图8 Guaymas盆地热液油气生成和运移模式图(修改自文献[185])

Fig. 8 Schematic diagrams showing the generation and migration of hydrothermal hydrocarbons in the Guaymas Basin (modified after reference [185])

a. Guaymas盆地热液烃运聚过程; b. 其他可能的情景

型火山活动主要发生于火山喷发主体期之前[188],数值模拟结果显示侵入作用下南非 Karoo 盆地可能已生成 $(2.7 \sim 16.2) \times 10^{12}$ t CH_4,挪威 Vøring 盆地和 Møre 盆地则产生 $(0.6 \sim 3.5) \times 10^{12}$ t CH_4[187]。印尼 Lusi 泥火山的富有机质的中始新统—下渐新统 Ngimbang 组黑色页岩(*TOC* 为 1.6%~14.6%)在全新世岩浆流体烘烤下,发生热变质反应,烃类与 CO_2 生成量大幅提升[189]。

深部热液流体会携带大量的富氢流体和过渡金属元素,这些过渡金属元素对烃类生成的催化作用极为重要[190-191]。过渡金属元素(Fe, Cr, Co, Ni 和 Cu 等)的 3d 电子层都处于未充满状态,对气体和有机质具有强烈的吸附作用,并可催化有机质中 C—C 键、C—S 键、C—O 键的断裂,从而达到使裂解反应加速、缩短反应时间及改变反应机理的催化目的[192-196]。富氢流体的加氢效应会进一步释放生烃潜力。在含水热解实验中,加氢过程将会极大促进烃类生成。沥青产率随温度升高呈单调递增趋势,其中加氢还原条件下产率提升了多个数量级,尤以未成熟湖相有机质响应最为显著[93]。此外,催化加氢实验提供了一种从烃源岩和原油族组分中提取生物标记碳氢化合物的独特方法,且对其异构体分布的影响极小[197]。与索氏萃取法相比,这种方法与催化加氢法一起可从成熟—过成熟阶段的固体沥青中释放出更多的可萃取有机物[105, 198-199]。

4.4　热液控藏过程

热液油气系统与传统沉积盆地冷成因系统存在本质差异。在热液体系中,有机质的输入、沉降、热成熟、生-排烃及运移等过程往往在极短的地质时限内近似同步完成[27]。系统中的挥发分和脂肪族组分提供了还原介质,而重质组分则易与矿物发生共沉淀。如图 8 所示,热液烃的运聚存在两种端元机制:① 开放体系下的耗散模式(以 Guaymas 盆地为典型),深部热源驱动热液渗入浅层未固结细粒沉积物,促使有机质快速生烃并排泄至水柱中,部分重组分在喷口周围因激冷而沉淀,轻组分则通过扩散与生物降解散失;② 封闭体系下的成藏模式,当上覆存在致密盖层时,热液生成的石油注入多孔储集层,随着流体滞留时间的延长及温压降低,油-水-热液混合物发生相分离并聚集成藏[185]。

揭示油气成藏机理是优选有利勘探区、落实地质储量的核心依据[200-214]。岩浆-热液活动并非孤立的地质事件,而是贯穿并深刻制约油气从生成、运移到聚集的成藏全过程[215]。据此,本文提出热液控藏机制,即岩浆-热液作用控制了油气的生成、运移和聚集(图 9)。在烃源岩的形成过程中,岩浆-热液活动能够提供丰富的营养物质,促进初级生产力的勃发[216]。同时,其释放的大量 CO_2 和 H_2S 有助于维持还原环境,促进有机质的保存。在富有机质烃源岩形成之后,深部热液流体的到来还将可能促进烃源岩的二次生烃,类似催化加氢机制。另外,热液作用下的费托合成和碳酸盐矿化等机制有助于无机作用形成短链烷烃。这些无机短链烃和有机大分子烃的混合使得油气成因变得

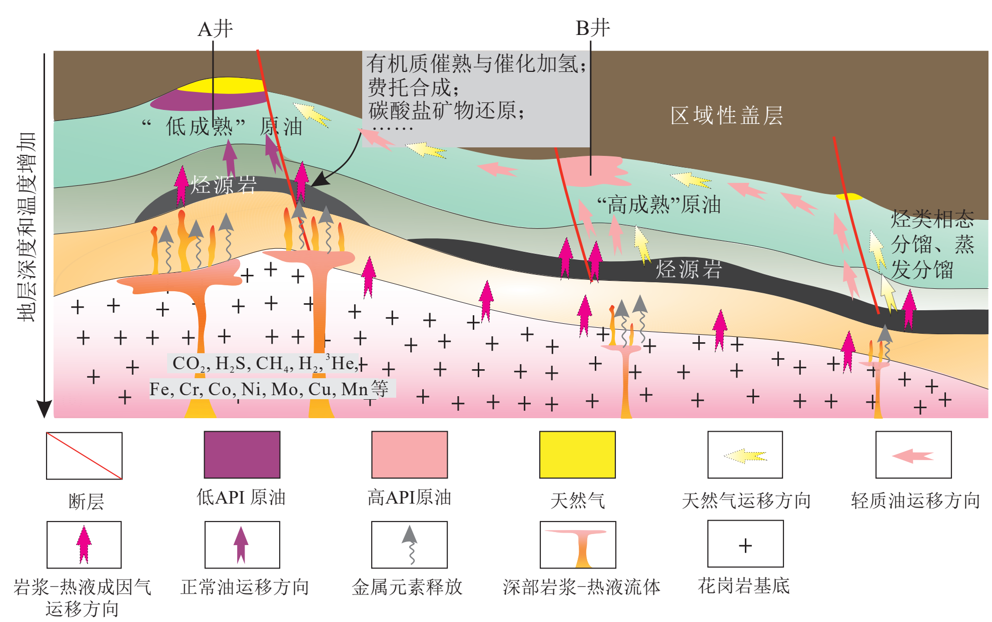

图 9　热液控藏机制示意图

Fig. 9　Conceptual model of hydrothermal-controlled hydrocarbon accumulation

API. 美国石油学会制订的原油相对密度单位

更为复杂。这为沉积盆地中的气体来源提供了一些启示。比如,在岩浆-热液活动极为活跃的盆地,其自身可携带一定量的幔源CH_4,加上快速催熟有机质形成的热成因CH_4,足以对原始油气分布格局产生较大影响。除此之外,当油气进入圈闭并聚集成藏后,后期的深部热液流体将会改变原始油气藏的相态,比如热液流体的萃取作用会导致轻质和重质组分的分异,而热液流体的蚀变作用会导致重烃组分的增加,甚至增加沥青质含量。这些过程容易导致油藏呈现为“高成熟”和“低成熟”的假象(图9)。

值得注意的是,岩浆作用对沉积盆地油气藏可产生显著的负面效应[20]。其影响主要体现在破坏储层物性(孔隙度与渗透率)并引发油气热裂解,在岩浆侵入已聚集油气的储层或尚未成熟、仍处于生烃阶段的烃源岩时尤为显著。此外,岩浆作用若发生于油气充注之后,将对油气保存产生不利影响[20]。例如,四川盆地储层中发现的油裂解甲烷与焦沥青,即为峨眉山大火成岩省相关热液活动与附加热效应的伴生产物[21]。总体而言,沉积盆地的岩浆-热液作用对储层、盖层和圈闭的形成,以及油气的运移和保存均可具有负面作用[19]。因此,跨圈层的岩浆-热液流体对油气资源兼具建设性与破坏性双重作用。在后续研究中,应立足于系统平衡的思维,深化超深层油气勘探与热液控藏理论的融合。

5 结论

1) 热液烃包括热液形成烃和热液改造烃,广泛分布于海底和陆地热液系统中。热液形成烃以有机质热催熟为主,同时伴有无机成因的短链烃混合。由于有机质热催熟是一个快速过程,所以其烃类产物往往具有未成熟的特征。热液改造烃常见于沉积盆地,特指岩浆-热液流体对含油气-矿产系统中的原始油气的蚀变和萃取作用。热液烃的成因判识需综合构造、成岩矿物和地球化学指标等。常用分子标志物指标表明,热液烃涵盖了低至高成熟、生物降解和燃烧等过程的典型地化特征,这些特征有助于实现热液改造程度的定量评价。

2) 热液控藏机制主要体现在深部岩浆-热液流体对沉积盆地内烃类的生成、运移和聚集全过程的控制。具体为:岩浆-热液活动有助于沉积盆地内热成因和无机成因烃类的形成与排出;岩浆-热液流体的萃取与蚀变作用会改造原始油气藏并发生组分分异,其热动力学机制倾向于驱动烃类到具备良好条件的圈闭中聚集成藏。热液控藏过程会极大地改变油气藏相态,影响盆地级别的油气分布。热液控藏理论与油气勘探的深入结合,有助于解释岩浆-热液活动活跃的沉积盆地中的油气系统分布特征,比如塔里木盆地、四川盆地、渤海湾盆地和松辽盆地等。

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