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特提斯构造域海底流体逃逸活动特征及其控制因素

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摘要: 海底流体逃逸活动会显著地改变海底地形地貌, 产生麻坑、泥火山等地貌和冷泉羽状流现象。特提斯构造域是世界上油气最集中的构造域, 流体逃逸活动广泛发育, 形成的复杂流体逸出结构, 对海洋油气勘探、全球气候变化研究等方面具有较好指示作用。本文选取特提斯构造域主要海域, 系统总结其海底流体逃逸活动特征, 发现特提斯构造域海底流体逃逸活动多分布在被动大陆边缘和弧后裂谷盆地等地质背景中, 其中地中海、黑海和南海广泛发育海底冷泉、麻坑和泥火山等流体逃逸特征, 而波斯湾和澳大利亚西北部近海大量发育碳酸盐岩。海底流体逃逸活动主要受控于活动断裂、沉积物超压、地震活动、海平面变化、潮汐活动和海底滑坡等海洋与地质因素。在不同海域, 流体来源也不尽相同（热成因、生物成因以及天然气水合物分解）, 大多数通过断层、泥火山和气烟囱等通道运移。建议重视对特提斯构造域海底流体逃逸活动发育区的调查和探测, 深入分析与之相关的海底流体逃逸地貌发育机制, 以及其特殊海域背景下的海洋与地质因素控制作用, 总结建立其海底流体逃逸活动模式及相关理论。

关键词: 特提斯; 流体逃逸; 天然气水合物; 油气勘探; 冷泉
中图分类号: P736.1　　　**文献标识码:** A

Characteristics and controlling factors of submarine fluid escape in Tethys tectonic domain

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Abstract: Seabed fluid escape may significantly change the seafloor topography, resulting in some geomorphic features such as pockmarks, mud volcanoes and cold seep plumes. The Tethys tectonic domain, the most hydrocarbon-rich domain in the world, hosts substantial fluid escape-related structures that can act as good indicators for offshore hydrocarbon exploration and global climate changes. Based on previous researches of major sea areas in the Tethys tectonic domain, this paper systematically summarized the characteristics of the seabed fluid flow, which shows that the seabed fluid escape activities of the Tethys tectonic area are mostly distributed in passive continental margins and back-arc rift basins. Seafloor manifestations of fluid escape including submarine cold seeps, pockmarks and mud volcanoes, are widely distributed in the Mediterranean Sea, the Black Sea and the South China Sea, however, massive carbonate-related structures are the prominent seabed fluid escape features in the Persian Gulf and the northwestern shelf of Australia. Seabed fluid flow is a dynamic process in the Tethys tectonic domain. The main marine and geological factors controlling fluid escape include active faults, sediment overpressure, seismic activities, sea-level changes, tidal activities and seabed landslides. Fluids are sourced from different intervals (thermal, biogenesis, and natural gas hydrate decomposition) in different sea areas, and the migration of fluids is mostly through fault planes, mud volcanoes and gas chimneys to the seafloor. To summarize and establish the model and theory of seabed fluid escape, it is suggested that more attention should be paid to the investigation and detection of the development areas of the seabed fluid escape activities in the Tethys tectonic domain. Moreover, the further analysis of the mechanism of the

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fluid escape-related geomorphic features, as well as the marine and geological controls in the special oceanic regions will provide basic support for the subsequent research.

Key words: Tethys; fluid escape; gas hydrate; oil and gas exploration; cold seep

海底流体逃逸活动在大陆边缘海域普遍发育[1-2]。以往以油气勘探为主的大多数地震数据主要聚焦于海底中深部目的层，而且浅地层成像的分辨率不高，导致海底聚集型流体逃逸活动研究相对较少[3]。近些年来，海底流体逃逸现象的研究表明，逃逸流体多通过断层、管道、气烟囱等通道运移，进而在海底渗漏逸散，形成海底泥丘、麻坑、泥火山和碳酸盐堆积等地形地貌和活动冷泉羽状流现象[1-2, 4-7]。海底流体逃逸活动的深入研究一方面可用于指示从储层到海底的流体逃逸运移体系[8]；另一方面则对海底斜坡稳定性、海洋生态系统研究、全球碳循环和天然气水合物的勘探和开发等具有重要意义[1, 5, 9-12]。

特提斯构造域具有特殊的地质背景以及油气成藏条件，围绕其油气勘探一直是研究热点[13]。特提斯构造域的油气资源特别丰富，世界上常规油气约三分之二分布在特提斯构造域内[14]。在黑海、地中海和南海等特提斯构造域的主要海域，广泛发育麻坑、泥火山、海底活动羽状流、自生碳酸盐岩、冷泉生物群落等流体逃逸活动特征，可以很好地指示过去和现在的海底流体逃逸活动，是海洋油气与天然气水合物等能源勘探的重要指示标志[15-20]。尽管对特提斯构造域主要海域的流体逃逸活动研究越来越多[21-25]，但缺乏整体的分析与认识，对其控制因素和演化过程的理解仍然不够透彻。

本文在调研国内外特提斯构造域现有研究成果的基础上，选取相关典型海域，总结特提斯构造域不同地质背景下的海底流体活动特征，并从流体来源、运移通道及地质构造等方面来分析流体逃逸活动的控制因素，进一步探讨海底流体逃逸活动与油气及天然气水合物的关系以及存在的科学问题，为后续特提斯域海底流体活动、海洋常规油气、天然气水合物等非常规油气勘探以及全球气候变化等科学研究提供参考。

1 地质背景

特提斯构造域是欧亚大陆和冈瓦纳大陆板块之间相互作用的结果，记录了特提斯洋的形成、发展和消亡的整个过程[26]。特提斯构造域近东西走向，现如今的展布范围，东起澳大利亚东北部，经东南亚、中亚、中东直到南欧（图 1），不但包括造山

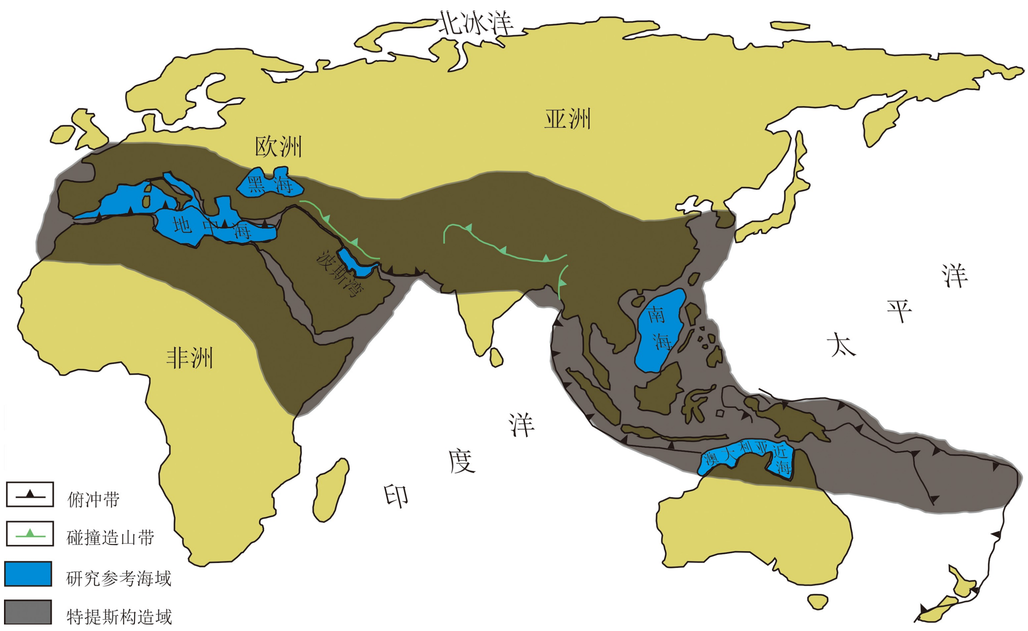

图 1 特提斯构造域展布范围

据 http://tethys.ac.cn。

Fig.1 The distribution of Tethyan tectonic domain

From http://tethys.ac.cn.

带, 而且也包含相关海域和沉积盆地, 如地中海、黑海、波斯湾、中国南海、澳大利亚西北部近海等。特提斯深水盆地群发育在非洲板块、欧亚板块和澳大利亚板块之间的区域, 其盆地发展演化过程的早期处于被动大陆边缘的伸展背景,后期受到碰撞造山影响而处于挤压背景[27]。特提斯构造域具有特定的构造和沉积环境, 在地史时期位于冈瓦纳大陆和欧亚大陆两个被动大陆边缘之间的赤道热带、亚热带洋区, 生物繁盛, 沉积有机质特别发育, 泥质岩是主要的烃源岩, 而且在浅海沉积形成了大量的碳酸盐岩和盐岩, 形成优质的盐岩圈闭和碳酸盐岩储层[14, 28], 因而蕴藏丰富的油气资源。

随着海洋勘探程度逐年上升,以及海洋油气勘探开发技术的迅速发展,特提斯构造域相关海域的海洋油气资源逐渐引起各国重视,相继发现了很多大型油气田, 其储量和产量所占比重逐年加大[29]。目前, 除了在波斯湾发现大量大型油气田外, 在黑海也有发现[30-32]。一直以来, 地中海海域油气资源的勘探和开发都集中于地中海东部[33]。近年来, 东地中海的尼罗河三角洲盆地和黎凡特盆地成为天然气勘探开发的热点地区[34-37]。澳大利亚西北部近海最近也有重大发现, 油气资源开采潜力巨大, “富气贫油”是其最鲜明的特点[38]。而我国海洋油气资源开发还处于早期阶段, 深水油气资源主要分布在南海北部地区, 目前在珠江口盆地和琼东南盆地已实现深水油气勘探开发[39]。

特提斯构造域除了蕴藏着丰富的常规油气资源外, 也储存大量天然气水合物等非常规资源[40-42]。近年来, 海域天然气水合物勘探和开发逐渐受到重视, 在南海、黑海等海域进行了大量与天然气水合物相关的科学研究[16, 43-45]。研究发现, 冷泉羽状流、麻坑和泥火山等海底流体逃逸特征广泛发育在天然气水合物发育区[19-20, 40, 46-47], 证明海底流体逃逸活动与海域深部油气及天然气水合物分布之间密切相关, 水合物储层和逃逸气体均是富甲烷流体在异常孔隙高压地层释放和储存过程中的产物。

2　海底流体逃逸活动特征

近些年随着海洋探测技术的深入发展, 与海底流体逃逸活动特征相关的报道逐渐丰富起来。海底流体逃逸活动不仅会显著改变海底地形地貌[2], 形成泥火山、麻坑等, 而且会对海底附近的生物化学过程产生一定的影响, 产生自生碳酸盐岩、生物群落等, 剧烈的流体逃逸还会在上覆水体中形成羽状流[48]。

2.1　泥火山

泥火山是由剧烈的泥浆排放不断堆积形成的隆起微地貌[6](图 2a), 通常伴随着深部地下沉积单元的流体和气体排放[49-50], 若深部泥质上涌未刺穿海底则形成泥底辟。泥火山在世界范围内分布广泛, 主要在俯冲带和造山带附近发现[50]。各国对海底泥火山的研究始于海洋油气资源和海域天然气水合物勘探和开发工作[51], 近年来在地中海[52-54]、黑海[55-56]、南海[57-58] 以及巴伦支海[59] 等海域发现了大量的海底泥火山。

活跃的泥火山通常扎根于成熟的油气系统, 喷发出的气体主要是甲烷, 在其周围经常发现天然气水合物的富集[53], 可以与其他烃类渗漏一起指示潜在的深部丰富油气资源[60-61], 具有重要指示意义和研究价值。目前关于海底泥火山的形成机制已经进行了深入的讨论, 一般认为主要有 3 种成因机制: ①被动大陆边缘和深海平原的沉积物沉积速率极快, 如地中海沿岸[62-63]、挪威海[64]; ②主动大陆边缘区域的横向构造挤压[49]; ③天然气水合物分解, 如贝加尔湖[65]。此外, 不同时期海平面变化也可能影响泥火山的形成,如黑海[66]。

2.2　麻坑

麻坑一般被描述为下伏地层活动流体在海底渗漏逸散形成的侵蚀结构[6](图 2b), 呈圆形、椭圆形、长条形、彗星型、新月形以及不规则形态, 直径最大可达几千米, 深度可达几百米[2, 6, 67]。它们单独或随机成簇出现, 有些沿着断层走向排列[68]。麻坑可能会保持活跃状态, 长时间有气体从中缓慢逸出, 或者在间歇性喷发之间处于休眠状态[69]。在世界上的许多地区, 如地中海[70-71]、南海[24, 72]、非洲下刚果盆地[12] 等都发现了海底麻坑。自从 King 和 MacLean[73] 发现海底麻坑以来, 麻坑的形成一直被归因于逃逸流体的侵蚀作用, 通常与海底流体渗漏或赋存在海洋沉积物中的天然气水合物发生分解有关[2, 48]。然而也有学者分析认为, 生物活动也可能是麻坑形成的一种机制, 如在澳大利亚西北大陆架南部发现的麻坑[74]。海底麻坑对于海洋油气和天然气水合物资源勘探开发以及海底地质灾害研究具有重要指导作用, 因为其指示了大量气体从沉积物到海洋甚至可能进入大气的潜在途径[69, 75-76]。在富烃盆地中形成麻坑的流体来源可能是生物成因, 也可能是热成因[2, 77]。一些研究表明, 在地震发

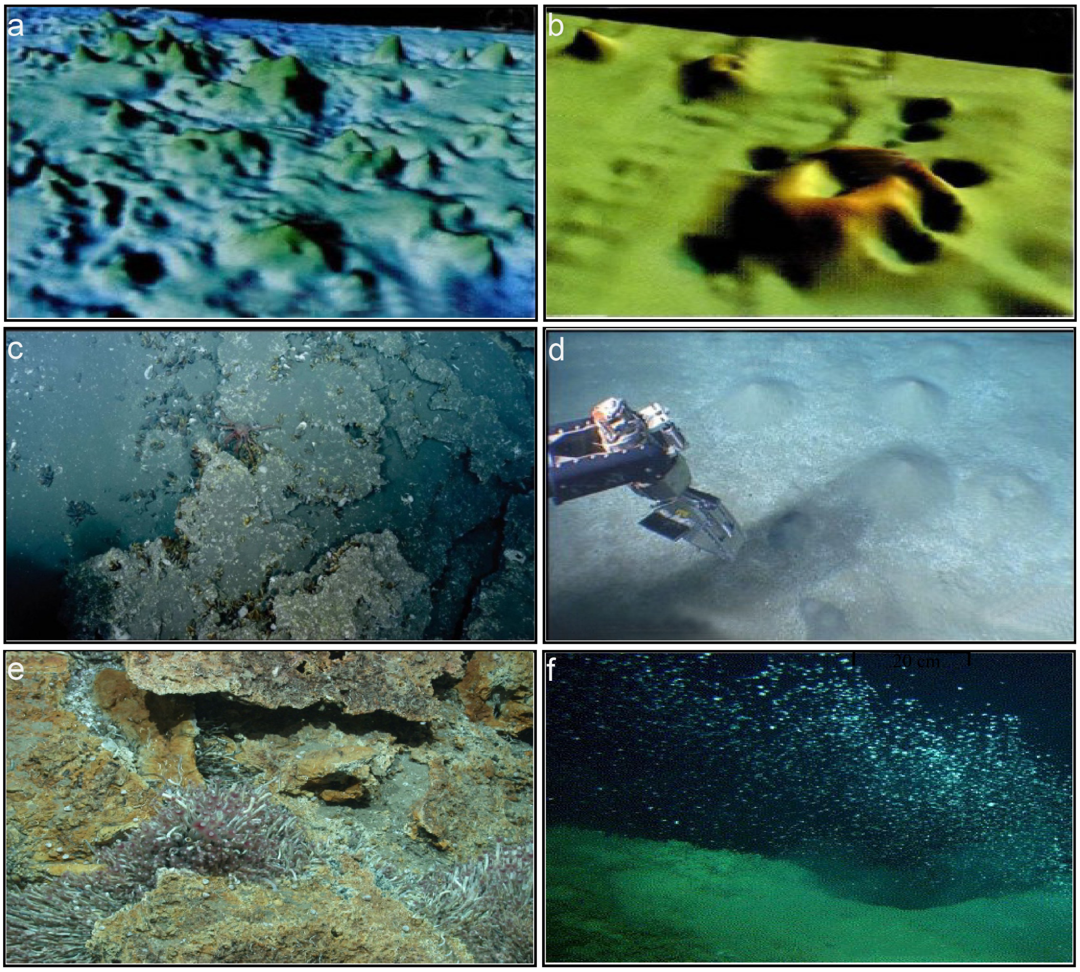

图 2 海底流体逃逸特征

a.海底泥火山[6], b.麻坑[6], c.碳酸盐岩[47], d.海底泥丘[83], e.生物群落[7], f.海底冷泉羽状流[59]。

Fig.2 Fluid escape features on seabed

a.submarine mud volcanoes[6], b. pockmarks[6], c. carbonate[47], d. submarine mounds[83], e. biotic community[7], f. submarine cold seep plume[59].

生前，海水温度升高，麻坑仍有气体逃逸，因此，麻坑可能是地震的先兆[78]。尤其是在一些大型麻坑发育区，地质构造活动活跃，可能会对海底基础设施造成危害[72]。

2.3 冷泉羽状流、碳酸盐岩、生物群落

海底冷泉是由水、碳氢化合物（天然气和石油）等，受地下压力梯度影响从沉积体中运移和排出形成的具有一定流速的流体[79-81]，且其周围温度通常无明显变化[82]。在冷泉发育区，除麻坑、泥火山等流体逃逸地貌和甲烷气体羽状流现象外，还伴生有自生碳酸盐岩和海底生物群落等相关特征[7, 47, 59, 83]（图 2c-f）。

冷泉活动已在世界许多地区发现并研究，例如南海[84]、墨西哥湾[85]、地中海[86]、黑海[87]、北海[88]、巴伦支海[59]、新西兰 Hikurangi 陆缘[89]、水合物脊[90]等。以甲烷为主要成分的气体通过断层、泥火山等运移通道进入海水后，形成海底冷泉羽状流[91]，是活动冷泉的重要指示标志，而部分冷泉区通常与天然气水合物的分解密切相关，所以海底冷泉羽状流可以间接指示海底沉积层中可能有天然气水合物赋存[92-93]。地球化学数据可以指示甲烷气体的成因，包括不同的形成环境和成因背景。热成因气体主要是由于地下深部富甲烷流体在流体超压作用下通过运移通道到达海底形成的，且多与深部油气藏相关，而生物成因气是由富含有机质沉积物中的微生物活动产生，水合物气藏与其关系密切。

在活动冷泉区，富甲烷流体会支持化学合成群落的发育和自生碳酸盐岩的形成。甲烷厌氧氧化（AOM）产生碳酸氢盐，从而导致自生碳酸盐沉淀，包括孤立的板状、层状、结壳状和结核状等，部分表面胶结大量贻贝等生物[94]。海底碳酸盐岩是海底冷泉流体活动和成岩演化过程的证据，同时也是海底冷泉生物和天然气水合物可能存在的重要指

示标志[41, 95]。在海底冷泉喷口,通常存在致密而多样的微生物和动物群落,排放的含气流体使其衍生成独特的生态系统[82, 96],所以海底生物群落也可以指示其周围存在活跃的流体逃逸活动。

3　主要海域海底流体逃逸特征

海底流体逃逸活动在特提斯构造域相关海域强烈且广泛,这些海域中油气资源和非常规能源(如天然气水合物)储量丰富,迄今已发现大量大型或超大型油气田,一直以来是许多国际学者研究海底流体逃逸活动的重点区域。

3.1　地中海

地中海位于非洲、欧亚和阿拉伯板块之间的相互作用带(图 3),主要受非洲和欧亚板块之间的碰撞以及相关俯冲作用的影响[3]。泥火山、麻坑和冷泉羽状流等海底流体逃逸活动广泛分布于地中海边缘[53, 71](图 3a, b),尤其在地中海东部[52-53, 69, 86, 97]。

20 世纪 70 年代后期, Cita 等[98]在地中海东部首次发现泥火山。此后的数十年内,地中海东部陆续发现大量泥火山,成为世界上泥火山发育最丰富的地区之一(超过 200 个)[50]。Camerlenghi 和 Pini[99]记录了多个地中海泥火山,包括在地中海东部海脊[61]、Anaximander 山脉[53]、阿尔沃兰海[100]、西西里岛近海[101]、尼罗河三角洲[97]和爱奥尼亚海等地发现的泥火山[102]。东地中海的大多数泥火山发育受海底天然气水合物分解和构造运动引起的天然气超压控制,非洲板块推动欧亚板块,导致气体和部分泥火山的压实[103]。其中, Anaximander 山脉自中新世以来,其泥火山分布和活动显著受控于走滑断裂和张应力作用[7, 104]。在地中海东部的麻坑多发育在活跃的泥火山、断层、大型海扇、增生楔体和海底塌陷等地质环境中,例如 Anaximander 山脉、Cobblestone 地区、Florence 隆起、Olimpi 泥火山区域、United Nation 隆起、Herodotus 深海平原、Sirte 深海平原、Eratosthenes 海山、尼罗河深海扇等[69-70]。近年来,在地中海中部浅水区发现的巨型麻坑(如 Zannone Giant Pockmark)喷发剧烈且持续性渗漏,证明地中海中部也存在较为活跃的流体逃逸活动[71]。研究分析认为麻坑可能受到边坡失稳(滑坡)、沉积物超压、高沉积速率、挤压构造以及孔隙压力升高等因素影响[69, 78, 97, 105]。在泥火山、麻坑和活动冷泉区通常发育大量碳酸盐岩,且与甲烷气体逸出有关[52, 86, 96, 106]。总体看来,在地中海,断层和泥火山是海底流体逃逸的主要运移通道[22, 78],而在尼罗河三角洲上坡,气烟囱是重要的运移通道[97]。此外, Bertoni 等[3]认为墨西尼蒸发岩抑制了正常压实孔隙流体的释放,其分布和变形可能会影响流体运移通道。

3.2　黑海

黑海起源于白垩纪,由被黑海中部高地隔开的东西子盆地组成,是世界上最大的缺氧海盆,在阿

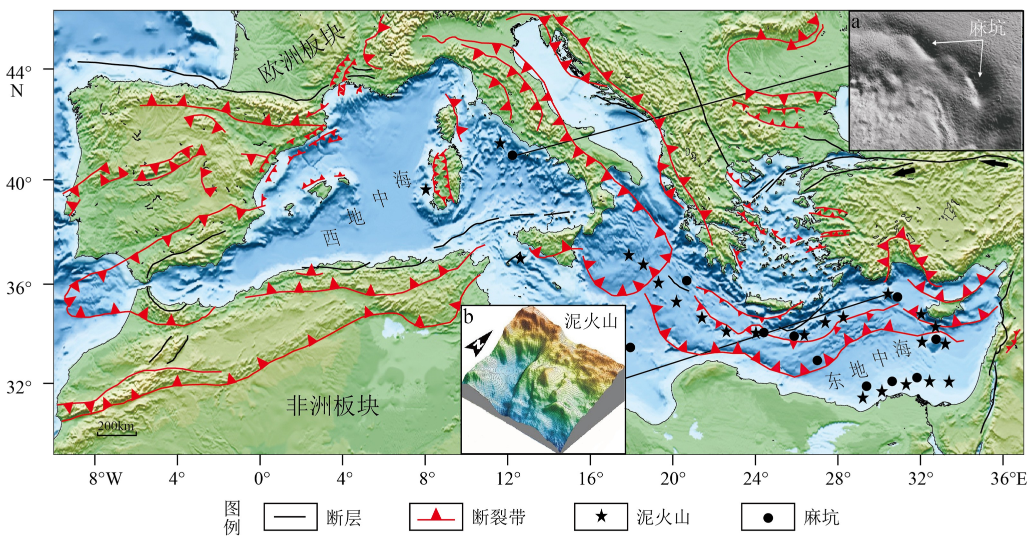

图 3　地中海及周边地区的构造背景和海底流体逃逸特征分布[52, 69-70, 103, 107]

a. Zannone 巨型麻坑[71], b. 喀山泥火山[53]。

Fig.3　The tectonic setting and distribution of fluid escape-related features in the Mediterranean Sea and surrounding areas[52, 69-70, 103, 107]

a. Zannone giant pockmark[71], b. Kazan mud volcano[53].

拉伯板块向北运动，安纳托利亚板块向西运动的作用下，目前正在经历挤压变形[108-112]（图 4）。黑海地区在浅水至深水环境中广泛发育泥火山、麻坑以及活动羽状流等海底流体逃逸活动特征[56, 87, 110]（图 4a-c），且被认为约有 68% 的区域适合天然气水合物的形成[23]。

迄今已探明的黑海泥火山约有 60 个，主要分布在黑海的中西部盆地和索罗金海槽，几乎所有泥火山都处于活跃状态[55]。Xing 和 Spiess[66] 对黑海中部的 6 个泥火山调查研究发现，泥火山活动可能与不同时期的海平面下降有关，而这似乎是黑海中部泥火山爆发的主要原因之一。冷泉在黑海分布广泛，大多数发育在小于 725 m（即高于天然气水合物稳定带（GHSZ））的水深中[87]，且不是随机分布，而是集中在某一特定区域，主要包括第聂伯河古扇、索罗金海槽、多瑙河深海扇、巴统渗透区、刻赤渗透区、俄罗斯和土耳其陆架等海域[42]。地球化学研究表明，黑海活动冷泉区的甲烷气体主要来源于富含有机物的厚沉积层（尤其是在陆架边缘三角洲的沉积物）中的微生物降解[42]，部分与天然气水合物失稳发生分解有关[113]，目前缺乏充足的证据表明存在热成因气体[16]。黑海活动冷泉主要受断层的影响[56, 87]，且天然气水合物稳定带或海底滑坡也会控制气体/流体的运移[16, 23]，如在 Vodianitskiy 泥火山调查取得的回波图显示，羽状流在水体中上升超过 1 300 m，主要原因是天然气水合物稳定带内的羽状流气泡在上升过程中形成了"水合物外衣"[114]。麻坑主要与甲烷气体渗漏活动有关，例如黑海西北部的第聂伯河古三角洲存在的 2 778 个气体逃逸活动较为活跃的渗漏点都是麻坑[87]。也有研究分析认为，在黑海东部土耳其陆架上发现的麻坑是由于地震活动引起的超压周期性变化产生的[115]。除断层、泥火山等流体运移通道外，气烟囱在黑海也很发育，与局部天然气供应的增加有关[23]。

3.3 波斯湾

波斯湾是 NW-SE 走向的狭长形海湾，介于伊朗高原和阿拉伯半岛之间，受扎格罗斯褶皱冲断带的影响[28, 117-118]（图 5）。波斯湾发育大量的碎屑岩、碳酸盐岩和盐类[117, 119]。与硅质碎屑岩储层不同，碳酸盐岩由于沉积环境和随后成岩作用的多样性而具有复杂的多尺度孔隙结构[120]，因而在波斯湾发现的大型、特大型油气田主要分布储层是碳酸盐岩，例如，南帕尔斯气田发现于 1990 年，是世界上最大的气田，其气藏是上二叠统达兰和下三叠统康安碳酸盐岩[30]。在地质历史上，波斯湾处于气候温暖的浅海环境，动植物丰富，构造稳定，沉积发育，因而油气资源丰富[28]。虽然它是世界上碳氢化合物储量最丰富的地区之一，但其麻坑、气体渗漏等逃逸特征在现在海底并不特别发育[121]（图 5a, b）。目前研究发现，逃逸的气体主要是热成因，但是也存在混合成因的可能[30]。距今最近的构造运动，包括与霍

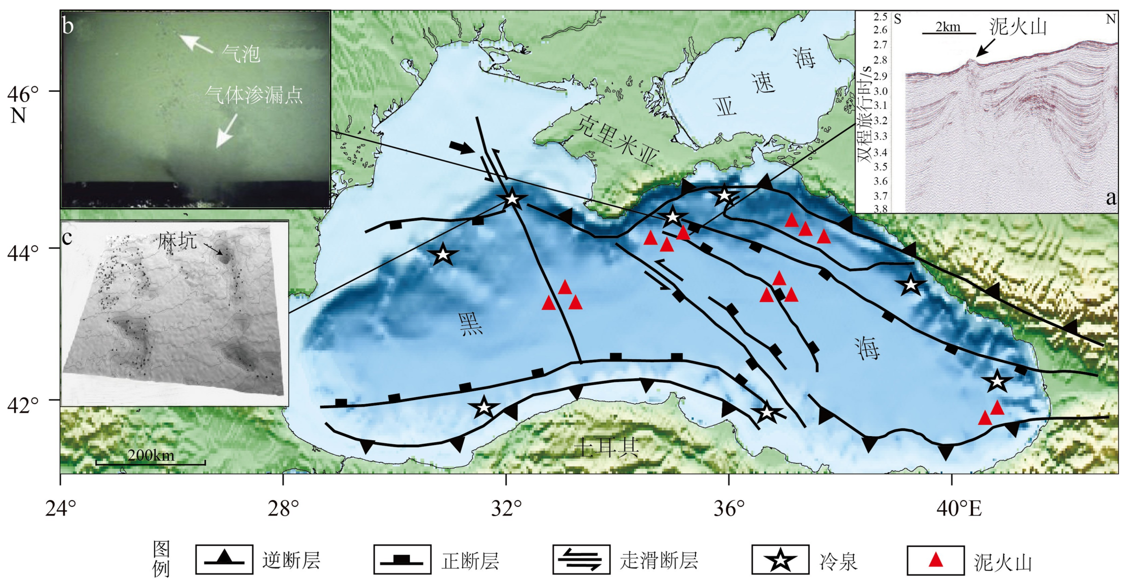

图 4　黑海及周边地区的构造背景和海底流体逃逸特征分布[42, 66, 116]

a. 泥火山[110], b. 海底逃逸的气体[56], c. 麻坑[87]。

Fig.4　The tectonic setting and distribution of fluid escape-related features in the Black Sea and surrounding areas[42, 66, 116]

a. mud volcano[110], b. the gas bubble escape from the gas vent[56], c. pockmark[87].

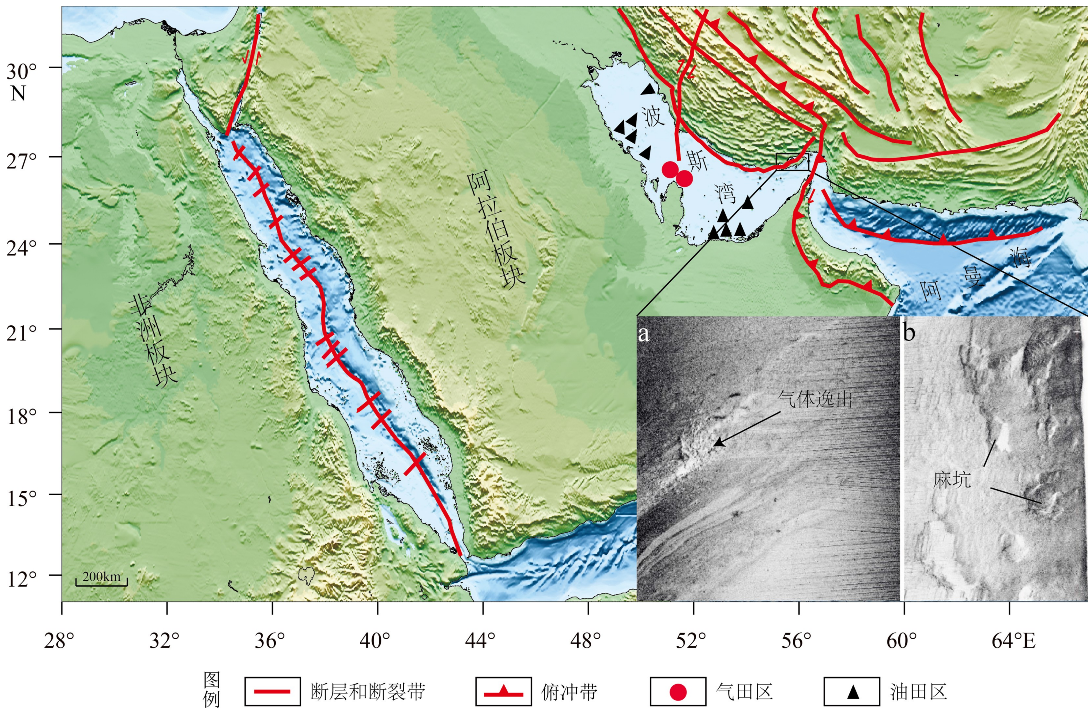

图 5　波斯湾及周边地区的构造背景和海底流体逃逸特征分布[118]

a.气体逸出[121], b.麻坑[121]。

Fig.5　The tectonic setting and distribution of fluid escape-related features in the Persian Gulf and surrounding areas[118]

a. the gas bubble escape from the seabed[121], b. pockmark[121].

尔木兹盐塑性流动有关的垂直运动，继续使波斯湾的沉积体系复杂化[122]。

3.4　南海

南海位于欧亚板块、太平洋板块和印度—澳大利亚板块交界处，是特提斯与太平洋构造域之间相互作用的关键区域[123]，具有张裂、走滑与汇聚增生楔等不同陆缘地质背景（图 6）。它是西太平洋面积最大的边缘海，最深处超过 5 000 m[46]。南海海底流体逃逸活动广泛且活跃，海底冷泉、麻坑和泥火山等典型逃逸特征广泛发育[72, 124-125]（图 6a-c）。逃逸流体主要通过泥火山、泥底辟、断层和气烟囱等通道运移[41, 43]，在海底形成大量流体逃逸特征地貌，指示潜在的油气和相关天然气水合物资源富集[126-127]。近些年来在台西南、东沙、神狐、西沙海槽、琼东南和南沙南部等海域都有发现冷泉活动[47]。其中，2015 年在琼东南盆地发现的“海马冷泉”，其下伏地层赋存大量天然气水合物[45, 128]。由于不同性质陆缘构造地质背景，泥火山（底辟）和麻坑等海底流体逃逸地貌在南海不同区域，分布和规模也有所不同。陈江欣等[6] 对南海北部和西部陆缘的泥火山、麻坑分布特征分析发现，麻坑、泥火山等流体逃逸地貌主要分布在构造活动较为活跃、沉积作用较为薄弱的近坡折带和大陆坡区域。在南海北部张裂大陆边缘，泥火山自东向西数量和规模逐渐变小，且主要集中在台西南盆地。而南海西部为走滑大陆边缘，构造活动活跃，流体逃逸特征分布较广，规模较大。中建南盆地的泥火山（底辟）的分布和类型与莺歌海盆地有明显不同，莺歌海盆地内部新近纪沉积层较厚，发育有大量的大型泥底辟[129]，而中建南盆地新生代沉积层较薄，经历晚白垩世或古近纪—渐新世裂谷向新近纪—第四纪裂陷后热沉降的构造演化[57]，泥火山活动可能与周边区域地震有关[58]。中建南盆地也是世界上最大的巨型麻坑分布区，连片分布的麻坑形态各异，部分麻坑受到地层内部气烟囱、倾斜断层和沉积边界的显著影响[72]，部分也受到深部底辟活动和南海西边界流底流的控制[125]。近期在南沙海域 Andu 海山附近发现大量巨型麻坑发育，推测其形成和演化与以活动断裂作为通道的流体逃逸活动有关[67]。

3.5　澳大利亚西北部近海

澳大利亚西北部近海位于被动大陆边缘[131]，其区域应力状态受复杂构造活动影响[132]（图 7）。赤道边缘水温高于 20 °C 时，有机生产力较高，在澳大利亚西北大陆架海底流体逃逸活动集中的区域发育大

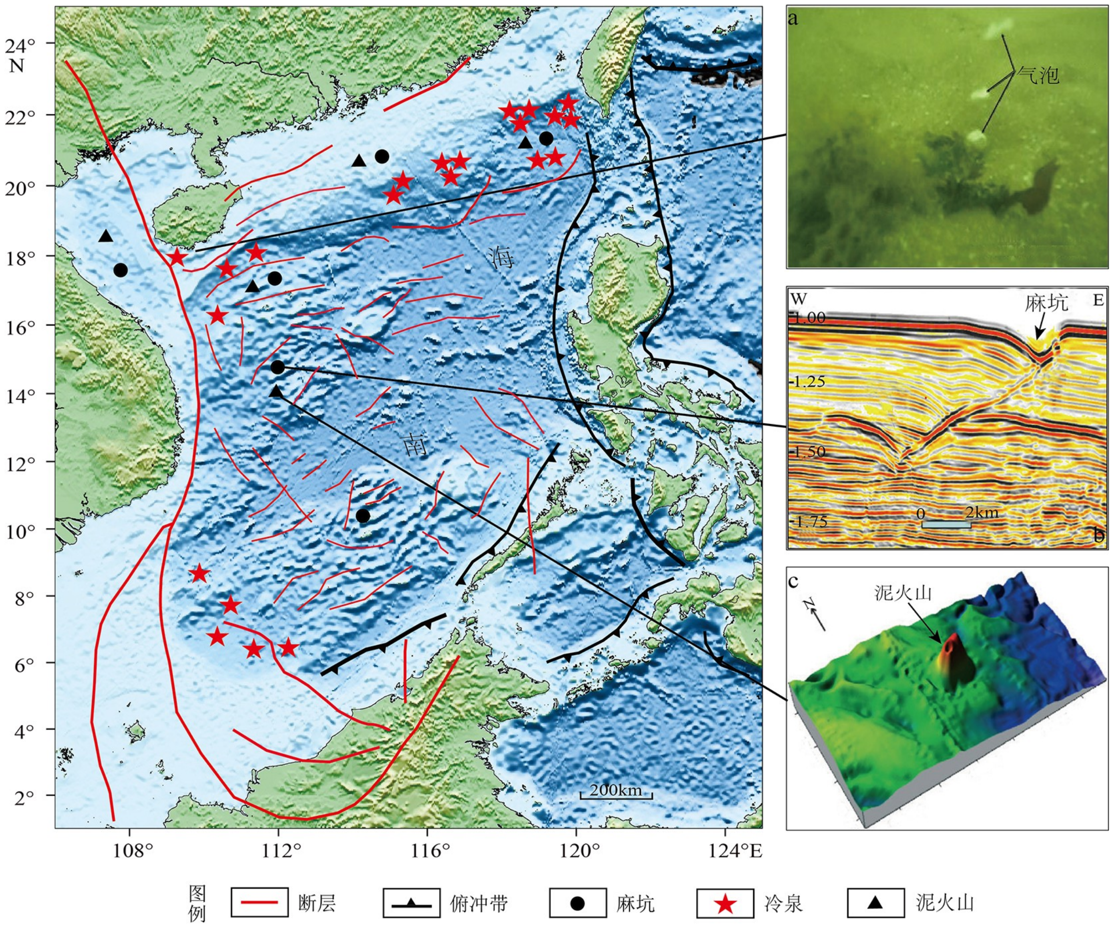

图 6 南海及周边地区的构造背景和海底流体逃逸特征分布[6, 47, 67, 130]

据南海地质地球物理图系-地貌图。

a. 海底生物和逃逸的气泡[124], b. 麻坑[72], c. 海底泥火山[125]。

Fig.6 The tectonic setting and distribution of fluid escape-related features in the South China Sea and surrounding areas[6, 47, 67, 130]

From the geomorphological map of the atlas of geology and geophysics of the South China Sea.

a. the gas bubble and benthic organism[124], b. pockmark[72], c. submarine mud volcano[125].

量形成于新生代的碳酸盐岩[21, 133]。在这些碳酸盐岩台地上，流体逃逸特征通常与潜在的烃类聚集或深层油气藏的渗漏有关[134](图 7b, c)，这会导致甲烷自生碳酸盐岩的沉积，促进碳酸盐建造的增长[135-136]。几十年来，在西北大陆架进行了多次渗漏调查，但仅在大陆架北部(Yampi 陆架)发现了较为活跃的烃渗漏点，其受新近纪碳酸盐岩层序沉积和中新世晚期构造活动控制形成[74, 135, 137]。与在硅质碎屑或深水环境中观察到的渗流特征相比，Yampi 陆架上的流体逃逸活动受碳酸盐沉积速率低和潮汐活动的影响，不利于泥火山、大型麻坑的形成[135]。同时自中新世以来，澳大利亚西北大陆架南部的碳酸盐台地上，陆源沉积物输入和沉积速率低，因而有学者分析认为南部麻坑的形成难以用海底流体逃逸活动解释，更可能与生物活动有关[74]。逃逸气体主要是热成因，但是 Rollet 等[134] 对阿拉法拉海浅层天然气和流体运移的研究表明，其逃逸气体存在混合成因的可能。通常断层控制着地下单元碳氢化合物的运移[21, 137]，但在部分地区，海平面变化是其沉积演化的主要控制因素，断层构造仅在局部影响中新世碳酸盐岩的堆积[138]，除此之外还发现盐底辟会导致海底流体逃逸活动的集中发生[21]。

4 海底流体逃逸的控制因素

基于对特提斯构造域主要海域研究结果的分析，对其海底流体逃逸活动特征、流体来源、运移通道及其地质控制作用总结如表 1 所示。总体上，特提斯构造域各海域海底流体逃逸活动广泛发育，但是活动机制复杂，难以用统一的地质模式进行解释，其一般规律和存在的科学问题，分析如下：

(1) 即使在相同陆缘地质背景下，不同海域的

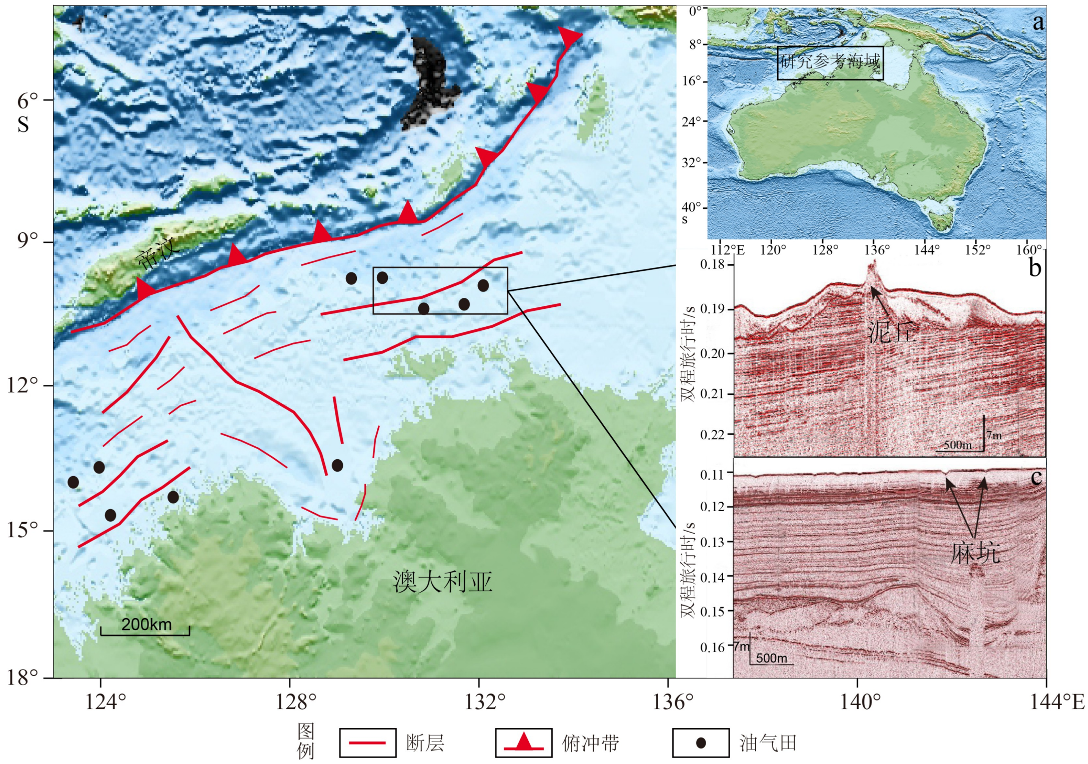

图 7　澳大利亚西北近海及周边地区的构造背景和海底流体逃逸特征分布[139-142]

a. 研究参考区域，b. 泥丘[134]，c. 麻坑[134]。

Fig.7　The tectonic setting and distribution of fluid escape-related features in the offshore northwest Australia and surrounding areas[139-142]

a. the reference region of research, b. mound[134], c. pockmark[134].

表 1　特提斯构造域海底流体逃逸

Table 1　Seabed fluid escape in the Tethys tectonic domain

研究区域	构造背景	主要逃逸特征	流体来源	运移通道	地质控制作用	主要参考文献
波斯湾	裂谷盆地	碳酸盐岩	热成因	断层	褶皱活动	[121-122]
地中海	俯冲带、被动大陆边缘	泥火山、麻坑、活动冷泉	热成因、生物成因、天然气水合物分解	断层、泥火山、气烟囱	海底滑坡、沉积物超压、高沉积速率、挤压构造、孔隙压力升高	[3,86,103]
黑海	弧后裂谷盆地	泥火山、麻坑、活动冷泉	生物成因、天然气水合物分解	断层、泥火山、气烟囱	海底滑坡、海平面升降、活动断层、海底峡谷、地震活动	[16,114]
南海	主动、被动与走滑大陆边缘	泥火山、麻坑、活动冷泉、碳酸盐岩	生物成因、热成因、天然气水合物分解	断层、泥火山、气烟囱	地震活动、深部底辟运动、倾斜断层和沉积边界	[44,47]
澳大利亚西北近海	被动大陆边缘	碳酸盐岩	热成因	断层	断层、海平面升降、潮汐活动	[21]

流体逃逸活动特征仍然差异较大。在地中海边缘及相关弧后盆地发育大量冷泉羽状流、泥火山、麻坑以及冷泉碳酸盐岩等[7, 86, 104, 143]。黑海为弧后裂谷盆地，富含有机物的沉积物在陆架边缘以及三角洲沉积[42]，广泛分布麻坑、泥火山和活动冷泉等海底流体逃逸地貌。南海具有多种陆缘地质背景，发育大量与冷泉流体活动相关的地貌特征（如麻坑、泥火山等）[6, 24, 41, 57]。与上述海域不同的是，澳大利亚西北部近海和波斯湾的泥火山、麻坑和冷泉活动特征不明显、不活跃[117, 121, 135]，主要是碳酸盐岩发育。

（2）海底流体逃逸活动需要充足气源，热成因、生物成因、混合成因或天然气水合物的分解均能提供充足的气源条件。在波斯湾和澳大利亚西北大陆架碳酸盐岩发育的地区，其气体主要是热成因气[30, 134]。而黑海的甲烷气体主要是由于含有机物的沉积物（尤其是在陆架边缘三角洲的沉积物）的快速沉积，以及随后的微生物降解产生[42]。地中海和南海甲烷气体来源广泛，包括生物成因、热成因与混合成因。天然气水合物失稳会导致流体渗漏，在南海、地中海及黑海已发现了大量与水合物生成和分解有关的流体逃逸活动，因而水合物分解也是逃逸气体的重要来源之一。

（3）海底流体逃逸活动受构造变形、海底滑坡、地震活动和海平面变化等多种海洋与地质因素主导或控制，并主要发育在地中海、黑海和南海等快速沉积、构造活动显著活跃的海域，通过运移通道（如断层、泥火山和气烟囱等）向海底渗漏逸散。地中海具有复杂地质条件和独特构造背景，天然气水合物分解与活动构造导致大量流体逃逸特征的发育[78, 103]。黑海的流体逃逸活动主要受到活动断层、海平面升降、海底峡谷和海底滑坡等的控制[55, 66, 87, 109]，部分地区也受地震活动的影响[115]。此外由于黑海为内海，故不同时期海平面变化会显著影响流体逃逸活动[66]。在南海发现的冷泉活动及与之相关的海底流体逃逸过程，与地震活动、深部底辟运动、活动断裂、倾斜断层和沉积边界等密切相关[58, 67, 72]。波斯湾沉积速率高，且受到扎格罗斯褶皱冲断带的影响[118]，沉积层变形明显。断层被认为是澳大利亚西北部碳酸盐岩生长的关键控制因素[21, 137, 144]，同时海平面变化、盐底辟构造或潮汐活动也会影响其形成和演化过程[21, 135, 138]。

5 结论与建议

（1）在特提斯构造域，各海域流体逃逸活动分布特征及活动特征差异较大。地中海、黑海和南海广泛发育活动冷泉及与之相关的麻坑、泥火山等逃逸地貌，而澳大利亚西北近海和波斯湾主要是碳酸盐岩发育。在不同海域，流体来源也不尽相同，大部分是热成因和生物成因，还有可能来源于天然气水合物的分解。

（2）特提斯构造域海底流体逃逸活动是一个复杂的动态过程，取决于多种控制因素，主要包括活动断层、沉积物超压、边坡失稳、地震活动等地质因素，同时潮汐活动、海平面变化等海洋过程也会影响或部分控制海底流体逃逸活动的形成。

（3）从研究和指示看，一方面特提斯构造域海底流体逃逸活动特征发育可能与油气田和天然气水合物分布密切，是油气及天然气水合物勘探研究的重要参考；另一方面流体逃逸活动释放的甲烷等温室气体，对全球气候变化的研究及资源与环境服务有重大意义。

建议重视对特提斯构造域海底流体逃逸活动发育区的调查和探测，综合利用地球物理数据（尤其是多波束）、水体资料和地震海洋学资料，全面了解其流体逃逸特征发育位置和规模，探讨其特殊海域背景下的海洋与地质因素控制作用，总结建立其海底流体逃逸活动模式及相关理论，为后续海域天然气水合物和油气资源的精准勘探开发、全球气候变化、海底灾害等研究提供重要参考。

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