引用格式：康玉柱.中国南海地块天然气水合物成藏条件探讨[J].油气藏评价与开发,2021,11(5):659-668.
KANG Yuzhu. Exploration of accumulation conditions of natural gas hydrate reservoirs in the South China Sea Block[J]. Petroleum Reservoir Evaluation and Development, 2021, 11(5):659-668.
DOI：10.13809/j.cnki.cn32-1825/te.2021.05.001

中国南海地块天然气水合物成藏条件探讨

康玉柱
（中国石化石油勘探开发研究院,北京 100083）

摘要：我国南海地块天然气水合物资源潜力巨大,目前已在南海北部神狐海域成功完成天然气水合物试采,取得了水合物勘探的重大突破,但其发育的地质条件、成藏因素、分布状态仍然不清,有必要进一步开展水合物形成条件及其分布的研究。笔者以南海油气勘查资料为基础,参考南海石油—天然气—天然气水合物已取得的成果,从沉积、构造、油气条件及水合物富集要素等方面,探讨南海天然气水合物成藏条件和分布规律。结果表明:①南海地块地壳厚度薄、热流值高,有利于有机质热演化;②中新生界发育三角洲、冲积扇、浊积扇、滑塌扇等沉积相类型,砂、泥呈互层状分布,可为天然气水合物提供良好成藏条件;③构造要素多样复杂,张性或张扭性断裂系统发育,可构成天然气运移通道;④发育生物气、浅层热解气、中深层热解气和油气田气等4类气源,为天然气水合物成藏提供良好的物质基础;⑤隆起与坳陷是天然气水合物富集成藏的有利部位。研究结果为天然气水合物勘探开发提供了指导,并为其他海域天然气水合物勘查提供科学依据。

关键词：天然气水合物;成藏条件;分布特征;南海地块;气源类型
中图分类号：TE51 **文献标识码**：A

Exploration of accumulation conditions of natural gas hydrate reservoirs in the South China Sea Block

KANG Yuzhu

(Sinopec Exploration & Production Research Institute, Beijing 100083, China)

Abstract: In China, the South China Sea Block has great potential of natural gas hydrate resources. At present, the pilot production of natural gas hydrate has been successfully conducted in the Shenhu area, the northern part of the South China Sea, indicating a major breakthrough in hydrate exploration. However, the geological conditions, accumulation factors and hydrate distribution are still unclear, so it is necessary to further study the formation conditions and distribution of natural gas hydrate. Based on the oil and gas exploration data and the achievements of oil, gas and natural gas hydrate in the South China Sea, the accumulation conditions and distribution of natural gas hydrate in the South China Sea have been discussed in the aspects of sedimentation, structure, oil and gas conditions and hydrate enrichment factors. The results show that: ① The thin crustal thickness and high heat flow value of the South China Sea Block are conducive to the thermal evolution of organic matter; ② The sedimentary facies of delta, alluvial fan, turbidite fan and slump fan are developed in the meso-Cenozoic, and the sand and mud are interbedded, which provides favourable conditions for gas hydrate accumulation; ③ The diverse and complex structure elements such as tensional or transtensional fault system can form migration channel for natural gas hydrate; ④ Four types of gas resources such as biogas, shallow-layer pyrolysis gas, middle-deep pyrolysis gas and gas field gas are developed, which provide a good material basis for gas hydrate accumulation; ⑤ Uplifts and depressions are favorable locations for gas hydrate accumulation. The results not only provide the guidance for the natural gas hydrate exploration and development, but also provide scientific evidence for the natural gas hydrate exploration in other sea areas.

Keywords: natural gas hydrate, accumulation conditions, distribution characteristics, the South China Sea Block, type of gas source

---

收稿日期：2021-02-29。
作者简介：康玉柱(1936年—),男,本科,教授级高工,中国工程院院士,从事石油地质与勘探研究工作。地址:北京市海淀区学院路31号,邮政编码:100083。E-mail: kangyz.syky@sinopec.com
基金项目：中国地质调查项目“重点地区构造体系及油气页岩气控藏条件调查”(DD20190085)。

天然气水合物是天然气与水在高压和低温条件下形成的一种固态结晶物质，其主要成分为甲烷[1-10]。全球天然气水合物资源潜力巨大，其热当量是煤、石油、天然气总热当量的2倍。天然气水合物埋藏较浅，一般赋存于海底0～1 500 m的沉积中，矿层厚度一般数十厘米至数百米，其能量密度非常高，1 m^3的水合物可释放出160 m^3的甲烷气体，是理想的清洁能源。1940年以来，美国、日本、加拿大、德国、印度等国家投入了大量人力物力开展天然气水合物研究[11-13]，在海底水合物沉积层和永久冻土层获取了大量的天然气水合物样品，水合物试开采试验也取得了较好成效。1990年以来，我国逐渐开展了天然气水合物勘探的探索，初步形成了勘探评价[14-21]、地球物理采集与预测[22-27]、钻探[28-30]、测井[31-33]、室内分析化验[34-39]、试采[40-48]等技术系列，为后续商业化开采积累了较为丰富的理论和技术储备。2017年5月，我国在南海北部神狐海域成功试采天然气水合物，初期日产气3.5×10^4 m^3，后期稳定日产气6 000～8 000 m^3，稳产62 d，稳产期世界最长，党中央及国务院发贺电祝贺。天然气水合物是全球重要清洁能源之一，笔者综合南海天然气水合物勘探现状，探讨水合物成藏条件和分布特征，以期为天然气水合物勘探开发和指导其他海域天然气水合物勘查提供科学依据。

1　南海地块及划分依据

南海海域面积约300×10^4 km^2。多年来，国内外许多专家学者把南海海域划分为几个相邻地块，如南海北部为华南地块、西部为印支地块、东部为菲律宾地块等（图1）。南海和相邻地块在地质构造特征

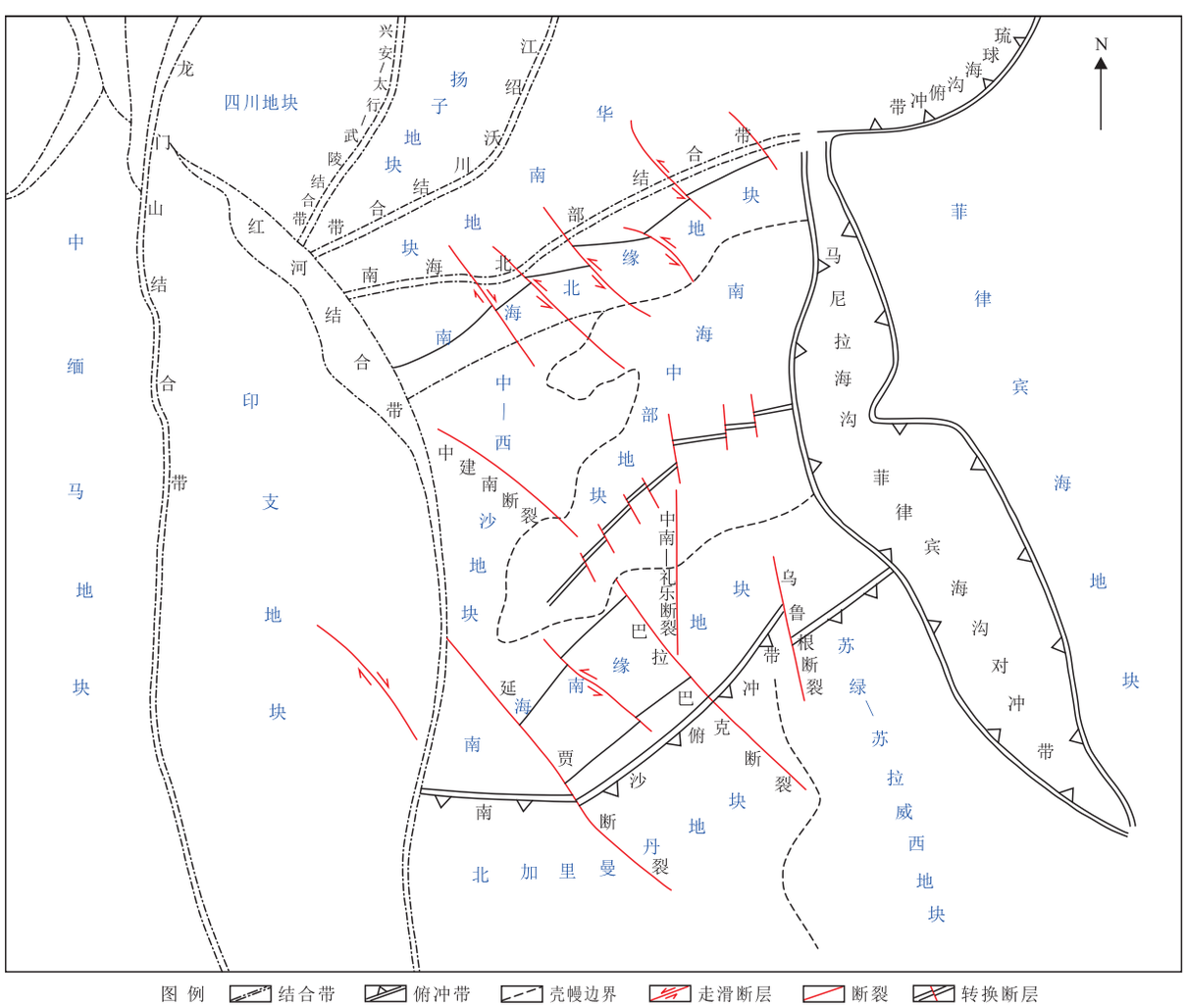

图1　南海地块边缘海盆地主要构造断裂及块体分布特征

Fig. 1　Distribution of main faults and blocks in the marginal sea basins of the South China Sea block

及演化等方面差异很大,在地质特征上南海地块(包括南海北缘、中—西沙、南海中部和南海南缘)与华夏、印度和菲律宾地块有较大差异,笔者首次提出南海海域是一个不可分割的独立地块——南海地块。其依据为:①南海地块的基底是由前寒武系变质岩组成,比相邻地块基底时代新;②南海变质基底基本轮廓是由中央向周缘自老变新的拼盘式褶皱基底,南海中央西沙群岛海域为前寒武纪变质基底,围绕该古陆周缘发育有加里东期、海西期和印支期褶皱变质基底[49];③ 南海地块地壳厚度较薄,为25~30 km,远比四周各地块薄;④南海地块古—中生界残缺不全,而新生界发育齐全且分布广泛,以海相和海陆过渡相为主,最厚达10 000 m;⑤南海地块新生代发生4次构造运动,期次多而强度大。

2 中国南海天然气水合物成藏条件探讨

南海地块天然气水合物成藏受多种地质因素的联合控制,机制复杂,但主要受地壳厚度、地层沉积条件、构造条件、气源条件4个因素的影响。

2.1 地壳厚度

比较南海周边深大断裂和莫霍面的深度[50],可以看出南海地壳远比周边地块薄(图2),反映出南海为

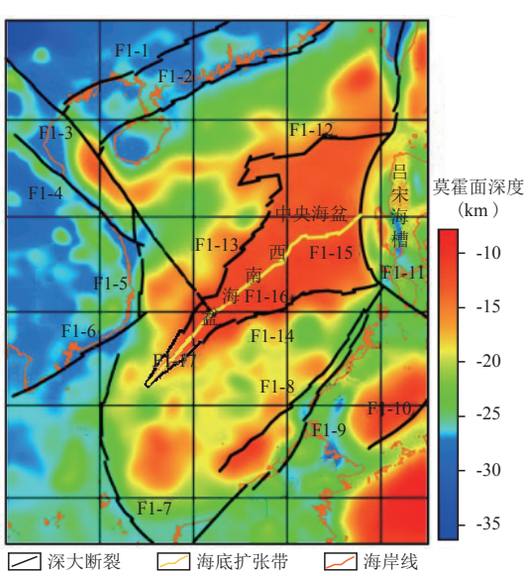

图2 南海深大断裂与莫霍面深度[50]

Fig. 2 Deep and large faults and Moho depth in the South China Sea[50]

下地幔高热度区。加之喜马拉雅期以来南海发生频繁的断裂活动和火山活动,导致南海成为高热流区。通过计算,南海热流值平均为75.9 mW/ m^2,比中国大陆热流值62.57 mW/ m^{2}高。所以,南海是具有高热流值的地区,高热流值加快地层和沉积物中的有机质热演化形成油气,且以天然气为主。

2.2 地层沉积条件

南海海域新生界沉积较齐全,即有海相又有陆相,为区内油气成藏创造了良好条件(图3)。另外,第四纪沉积条件和沉积环境有利,砂、泥共存并呈砂泥互层状分布,尤其发育三角洲、斜坡扇、浊积扇、滑塌扇等沉积相类型,有利于天然气水合物富集,为天然气水合物成藏提供良好场所[51-52]。

2.3 构造条件

南海地块构造条件十分复杂,自中生代以来经历了4次主要构造运动:印支运动、燕山早期运动、燕山晚期运动及喜马拉雅运动。多期构造运动使南海地块形成多种类构造体系:东西向—北北东向构造体系、北东向构造体系、北西向构造体系及青藏—缅甸—印尼反S型构造体系。多构造体系必然造成多期次、多方向、多性质的断裂活动。在南海北部,断裂系统以北东和北北东向为主,晚期受到北西向配套断裂切割,这套北西向断裂主要为张性或张扭性(图4),有利于油气运移,为深层天然气向上运移创造良好条件[53-55]。

2.4 气源条件

气源条件是形成天然气水合物的关键,目前认为主要发育4类气源:

1)生物气

世界上已发现的生物气储量为15.5×10^{12} m^3,占全世界天然气总储量的20 %。南海地块的北部和南部均发育了大型陆缘碎屑供给体系,具有较高的生物气生产率,为海底生物气资源奠定了良好的气源基础。

2)浅层热解气

2 000 m以浅的地层中热解气充足。中下中新统分布广,全区可见,为1套海相地层,烃源岩厚180~200 m,具较好生烃能力。另外,上渐新统—中中新统烃源岩,为滨海—浅海相烃源岩,厚度一般

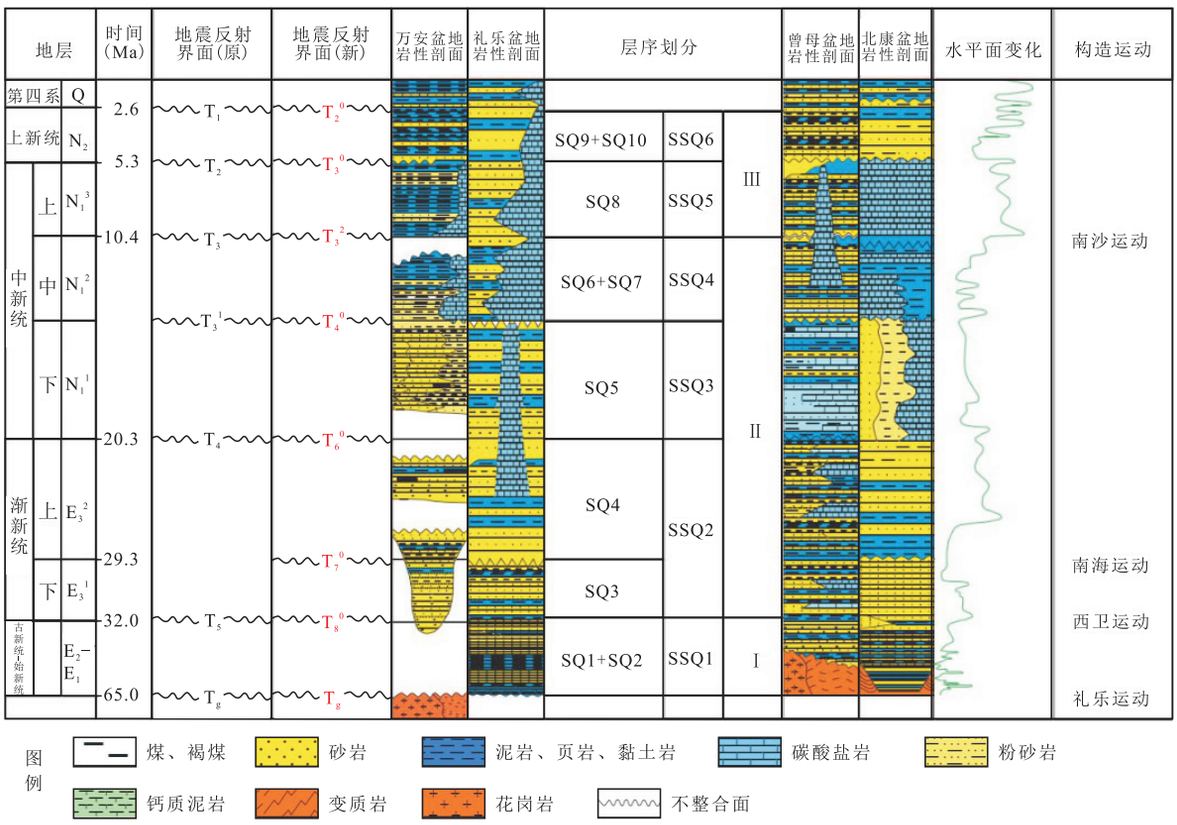

图3　南海海域新生代地层层序构成特征[52]

Fig. 3　Constitutive characteristic of Cenozoic stratigraphic sequence of Nansha offshore area[52]

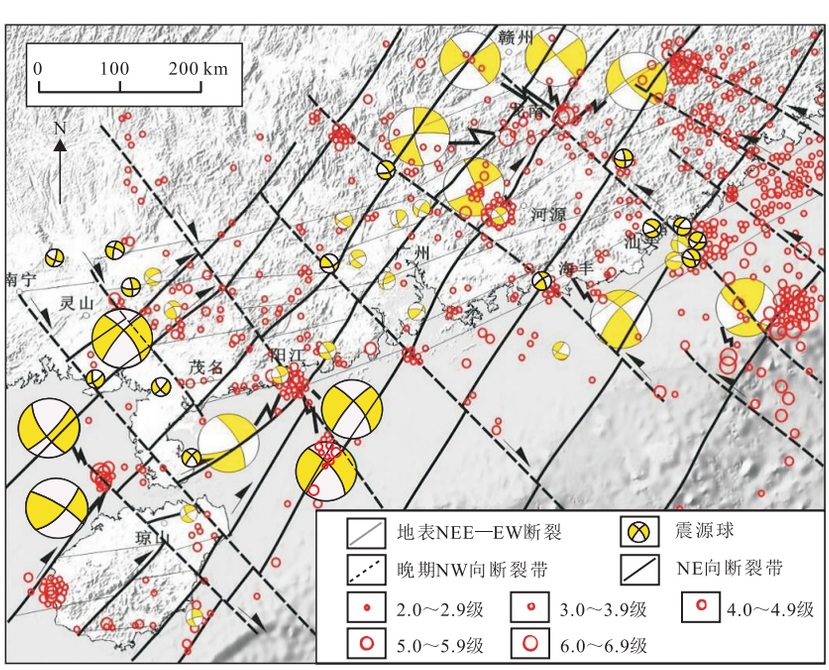

图4　南海北部和邻区活动断裂和地震分布

Fig. 4　Distribution of active faults and earthquakes in northern South China Sea and its adjacent areas

300～400 m，生油地球化学指标较好，有机碳普遍介于0.35 %～5 %。南海北部陆架外缘至深海盆地，腐泥质含量较高，以II型和少量I型干酪根为主。

3）深层热解气

①古新统—下渐新统烃源岩，沉积范围有限，主要分布在坳陷内，烃源岩厚度变化较大，一般200～300 m，生油地球化学指标良好，为中等烃源岩。在珠江口盆地中始新统为重要的区域性烃源层；在东海的平湖组和灵峰组上段，有机质丰度较高，分别为0.4 %和2.28 %。

②中古生界烃源岩，烃源岩厚度变化较大，一般200～300 m，生油地球化学指标较好，为中等烃源岩。在粤东沿岸地区，上三叠—下侏罗统海相页岩中有机碳含量达0.21 %～1.99 %。

4）油气田气

目前，南海海域新生界已发现了上百个油气田，且以气田为主，既有浅层油气田，又有中深层油气田，还会不断发现新的油气田，为天然气水合物成藏提供了丰富的气源。目前发现的天然气水合物藏与中深层油气田有密切关系。例如：南海北部神狐天然气水合物藏的深部对应于白云凹陷内部的有利区，在琼东南盆地陵17-2深水大气田之上对应发育了天然气水合物富集区。

总体上，生物气、浅层热解气、中深层热解气及油气田气等4类气源，是天然气水合物成藏的重要气源[55-56]，如图5所示，3 800 m以下文昌和恩平组油气藏为深部富集常规油气资源；在2 000～3 800 m珠江和珠海组为浅层油气藏；在300～2 000 m韩江组到第四纪沉积岩中发育浅层生物气和游离天然气；水合物分布于深水海底160～300 m的晚中新世—上新世未成岩深灰色细粒沉积物中。

3 天然气水合物分布特征

研究认为，沉积相与环境、构造条件是控制天然气水合物分布的主要因素[57-58]。

3.1 沉积相与环境

目前已经发现的天然气水合物，主要发育于细粒粉砂、粉砂质泥等沉积物中，其孔隙度与生物硅含量呈正相关。沉积速率越快、厚度越大，越有利于天然气水合物富集。三角洲、滑塌扇、浊积扇、斜坡扇往往沉积速率高，是有利于天然气水合物富集的沉积相类型。在地震剖面上，往往表现在相对整一的反射中发育断续的、略平行于海底反射的强反射；且往往和断裂反射、滑坡面反射构成相交关系（图6）。

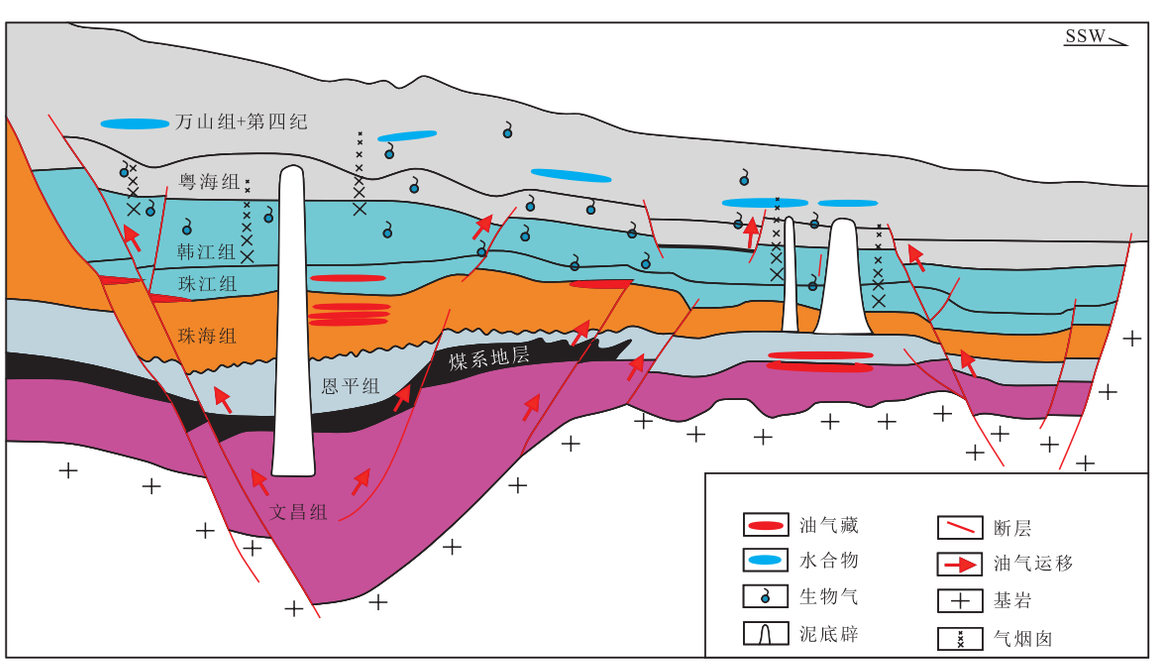

图5 珠江口盆地白云凹陷深水油气藏与生物气及海底水合物叠置分布模式

Fig. 5 Superimposed distribution mode of deep water reservoirs, biogas and submarine hydrate in Baiyun Sag, Pearl River Mouth Basin

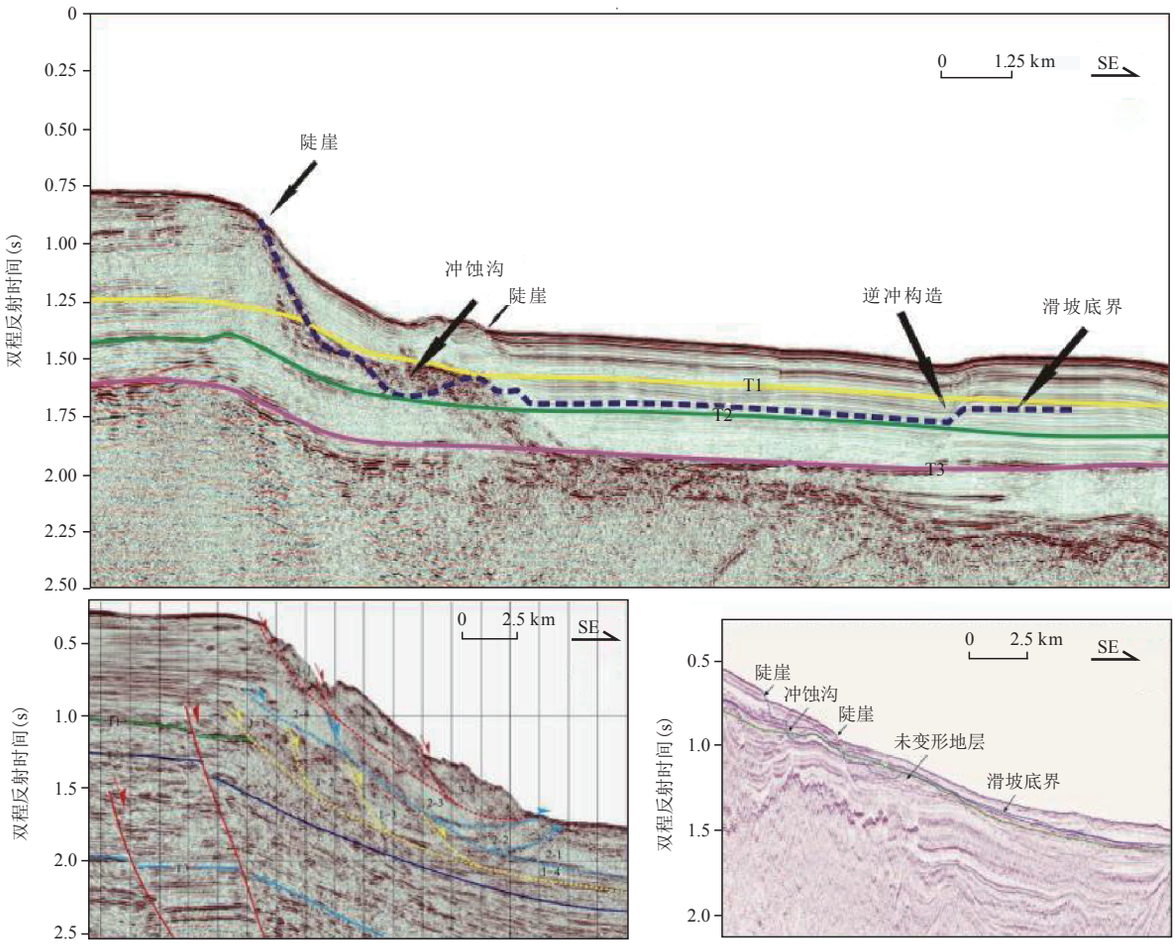

图6　典型似海底反射层的(BSR)反射和断裂、滑坡等构造现象的耦合关系

Fig. 6　Relation between typical bottom correlated reflector(BSR) and tectonic phenomena such as fractures and landslides

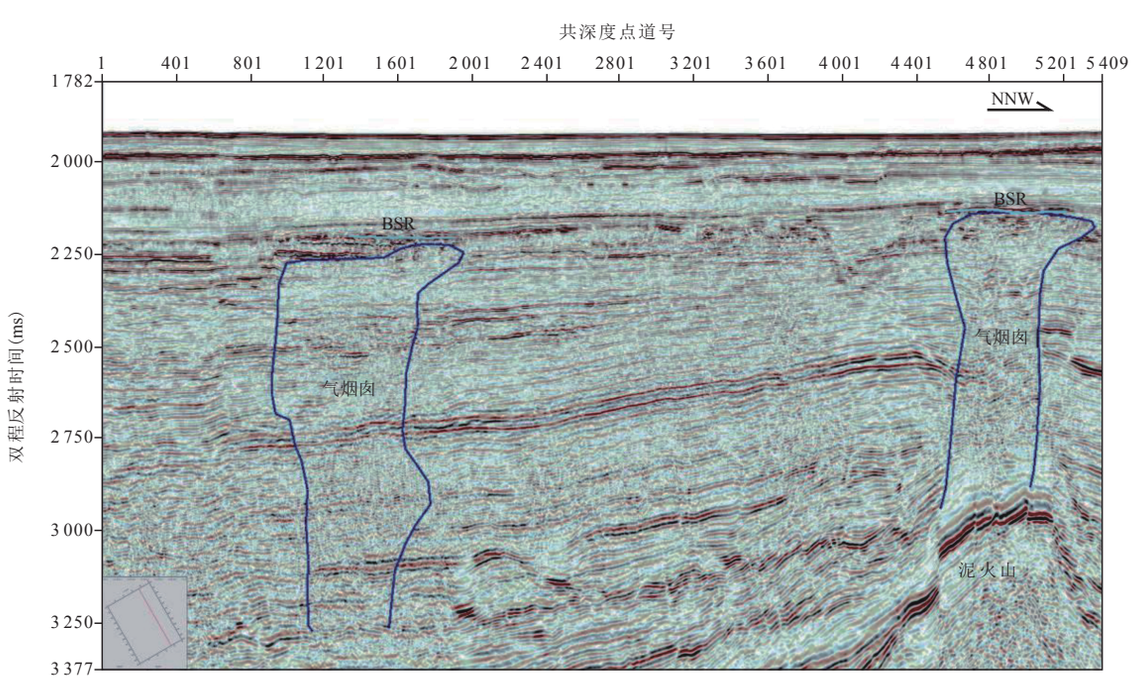

图7　气烟囱的地震响应特征

Fig. 7　Seismic response characteristic of gas chimney

3.2 构造条件

1）断裂构造

首先，断裂是运移通道。其次，构造活动形成的断裂及裂隙通道和局部正向构造是流体及天然气水合物成矿成藏的有利区带及场所[59]。

区内发育了多期、多类型、多方向、不同规模的断裂构造，以北东向及北北东走向断裂体系为主，后期又产生北西和北北西向的张性及张扭性断裂系统，使浅层及中深层热解气和油气田气，沿活动断裂向上运移，在海底形成天然气水合物并富集成藏。因此，泥火山、气烟囱等现象就是深部天然气沿断裂向上运移的表现（图7）。体现在浅层的BSR和深层的烃源岩之间往往通过断裂附近、或构造上部的杂乱空白反射予以沟通，这是构造活动形成垂向高孔渗带、深层烃源岩生成的烃类垂向运移、减弱波阻抗差的结果。

2）构造样式

南海地块构造样式丰富，隆起与坳陷普遍发育，内部发育褶皱带、断褶带、逆掩带以及背斜、断背斜、断块等次级构造，隆起与坳陷较发育的台西南、东沙南、神狐东、西沙海槽、西沙北、西沙南、中建南、万安北、北康北、南沙中、礼乐东地区是天然气水合物富集成藏的有利部位。

4 结论

1）南海天然气水合物资源潜力巨大，生物气、浅层热解气、中深层热解气及油气田气等是天然气水合物成藏的重要气源。

2）我国南海海域天然气水合物成藏条件十分优越，南海具有高热流值条件、沉积地层条件、构造条件、气源条件等有利成藏条件。

3）南海地块构造样式十分丰富，隆起与坳陷普遍发育，台西南、东沙南、神狐东等11个地区是天然气水合物富集成藏的有利区域。

参 考 文 献

[1] 沙志彬，许振强，付少英，等.珠江口盆地东部海域天然气水合物成藏气源特征探讨[J].海洋地质与第四纪地质，2019，39（4）：116-125.
SHA Zhibin, XU Zhenqiang, FU Shaoying, et al. Gas sources and its implications for hydrate accumulation in the eastern Pearl River Mouth Basin[J]. Marine Geology & Quaternary Geology, 2019, 39 (4): 116-125.

[2] 关进安，樊栓狮，梁德青，等.自然界天然气水合物勘探开发概述[J].新能源进展，2019，7（6）：522-531.
GUAN Jinan, FAN Shuanshi, LIANG Deqing, et al. An overview on gas hydrate exploration and exploitation in natural fields[J]. Advances in New and Renewable Energy, 2019, 7(6): 522-531.

[3] 付超，于兴河，梁金强，等.南海北部神狐海域不同类型水道及其天然气水合物成藏的差异[J].海洋地质与第四纪地质，2017，37（6）：168-177.
FU Chao, YU Xinghe, LIANG Jinqiang, et al. Types of sea-bottom channels and related gas hydrate accumulations in the Shenhu area, south China sea (SCS) [J]. Marine Geology & Quaternary Geology, 2017, 37(6): 168-177.

[4] 杨胜雄，梁金强，陆敬安，等.南海北部神狐海域天然气水合物成藏特征及主控因素新认识[J].地学前缘，2017，24（4）：1-14.
YANG Shengxiong, LIANG Jinqiang, LU Jingan, et al. New understandings on the characteristics and controlling factors of gas hydrate reservoirs in the Shenhu area on the northern slope of the South China Sea[J]. Earth Science Frontiers, 2017, 24 (4): 1-14.

[5] 张光学，梁金强，陆敬安，等.南海东北部陆坡天然气水合物藏特征[J].天然气工业，2014，34（11）：1-10.
ZHANG Guangxue, LIANG Jinqiang, LU Jingan, et al. Characteristics of natural gas hydrate reservoirs on the northeastern slope of the South China Sea[J]. Natural Gas Industry, 2014, 34(11): 1-10.

[6] 张金华，苏明，魏伟，等.海域天然气水合物富集成藏评价方法：以墨西哥湾AC818#1区域为例[J].地质科技情报，2019，38（4）：1-7.
ZHANG Jinhua, SU Ming, WEI Wei, et al. Enrichment and accumulation evaluation method of marine natural gas hydrate: A case of the gulf of Mexico Alaminos Canyon block 818#1[J]. Geological Science and Technology Information, 2019, 38(4): 1-7.

[7] 刘昌岭，孟庆国，李承峰，等.南海北部陆坡天然气水合物及其赋存沉积物特征[J].地学前缘，2017，24（4）：41-50.
LIU Changling, MENG Qingguo, LI Chengfeng, et al. Characterization of natural gas hydrate and its deposits recovered from the northern slope of the South China Sea[J]. Earth Science Frontiers, 2017, 24(4): 41-50.

[8] 梁前勇，赵静，夏真，等.南海北部陆坡天然气水合物区海水甲烷浓度分布特征及其影响因素探讨[J].地学前缘，2017，24（4）：89-101.
LIANG Qianyong, ZHAO Jing, XIA Zhen, et al. Distribution characteristics and influential factors of dissolved methane in sea water above gas hydrate area on the northern slope of the South China Sea[J]. Earth Science Frontiers, 2017, 24(4): 89-101.

[9] 王静丽，梁金强，沙志彬，等.南海北部琼东南海域气烟囱发育特征及其对水合物形成与分布的影响[J].海洋地质前沿，2017，33（3）：1-6.
WANG Jingli, LIANG Jinqiang, SHA Zhibin, et al. Development characteristics of gas chimney and its effect on

formation and distribution of natural gas hydrate in the Qiongdongnan Area, northern south China sea[J]. Marine Geology Frontiers, 2017, 33(3): 1-6.

[10] 张伟,梁金强,何家雄,等.南海北部神狐海域GmGS1和GmGS3钻探区天然气水合物运聚成藏的差异性[J].天然气工业,2018,38(3):138-149.
ZHANG Wei, LIANG Jinqiang, He Jiaxiong, et al. Differences in natural gas hydrate migration and accumulation between GMGS1 and GMGS3 drilling areas in the Shenhu area, northern South China Sea[J]. Natural Gas Industry, 2018, 38(3): 138-149.

[11] 杨木壮,何韵.南极半岛西侧别林斯高晋海陆缘含水合物系统及资源潜力[J].海洋地质与第四纪地质,2019,39(4):136-147.
YANG Muzhuang HE Yun. Gas hydrate system and resource potential of the continental margin of the Bellingshausen sea to the west coast of the Antarctic Peninsula[J]. Marine Geology & Quaternary Geology, 2019, 39(4): 136-147.

[12] 沙志彬,许振强,王平康,等.世界天然气水合物研究发展对我国加快推进其产业化的启示[J].海洋地质前沿,2019,35(8):1-10.
SHA Zhibin, XU Zhenqiang, WANG Pingkang, et al. World progress in gas hydrate research and its enlightenment to accelerating industrialization in China[J]. Marine Geology Frontiers, 2019, 35(8): 1-10.

[13] 王力峰,付少英,梁金强,等.全球主要国家水合物探采计划与研究进展[J].中国地质,2017,44(3):439-448.
WANG Lifeng, FU Sshaoying, LIANG Jinqiang, et al. A review on gas hydrate developments propped by worldwide national projects[J]. Geology in China, 2017, 44(3): 439-448.

[14] 冯强强,陶军,陈宗恒,等.天然气水合物调查区微地貌特征探测成果[J].地球学报,2019,40(2):314-318.
FENG Qiangqiang, TAO Jun, CHEN Zongheng, et al. Micro-topographic features detection in natural gas hydrate survey area [J]. Acta Geoscientica Sinica, 2019, 40(2): 314-318.

[15] 刘杰,杨睿,邬黛黛,等.琼东南盆地华光凹陷天然气水合物稳定带厚度的影响因素[J].海洋学报,2019,41(8):13-25.
LIU Jie, YANG Rui, WU Daidai, et al. Factors affecting the thickness of gas hydrate stability zones in the Huaguang Sag, Qiongdongnan Basin[J]. Acta Oceanologica Sinica, 2019, 41(8): 13-25.

[16] 朱一铭,陈晨,陈忠勇,等.天然气水合物沉积物分解过程中本构关系研究[J].新能源进展,2019,7(5):385-392.
ZHU Yiming, CHEN Chen, CHEN Zhongyong, et al. A constitutive model of hydrate- bearing sediments considering the hydrate dissociation[J]. Advances in New and Renewable Energy, 2019, 7(5): 385-392.

[17] 鲁晓兵,张旭辉,王平康,等.天然气水合物成藏动力学研究进展[J].中国科学:物理学,力学,天文学,2019,49(3):60-75.
LU Xiaobing, ZHANG Xuhui, WANG Pingkang, et al. Advances of formation dynamics of natural gas hydrate[J]. Scientia Sinica(Physica, Mechanica & Astronomica), 2019, 49(3): 60-75.

[18] 陈兵兵,杨明军,王大勇,等.天然气水合物分解沉积层内水流速度分布特性[J].中国科学:物理学,力学,天文学,2019,49(3):127-135.
CHEN Bingbing, YANG Mingjun, WANG Dayong, et al. The water flow velocity distribution characteristics in sediments with nature hydrate dissociation[J]. Scientia Sinica (Physica, Mechanica & Astronomica), 2019, 49(3): 127-135.

[19] 程聪,姜涛,匡增桂,等.天然气水合物系统特征及其对我国水合物勘查的启示[J].地质科技情报,2019,38(4):30-40.
CHENG Cong, JIANG Tao, KUANG Zenggui, et al. Characteristics of gas hydrate system and its enlightenment to gas hydrate exploration in China[J]. Geological Science and Technology Information, 2019, 38(4): 30-40.

[20] 丛晓荣,张伟,刘丽华,等.天然气水合物油气系统模拟新技术方法与应用[J].海洋地质前沿,2018,34(7):33-45.
CONG Xiaorong, ZHANG Wei, LIU Lihua, et al. New technology for gas hydrate petroleum system modeling and its application[J]. Marine Geology Frontiers, 2018, 34(7): 33-45.

[21] 陈宏文,梁世容.南沙海域曾母盆地的油气勘探开发现状[J].南海地质研究,2004(1):92-98.
CHEN Hongwen, LIANG Shirong. Progress of gas-oil prospecting at Zengmu basin, Nansha, South China Sea[J]. Gresearch of Eological South China Sea, 2004(1): 92-98.

[22] 孟大江,文鹏飞,张旭东.AVO反演在琼东南海域天然气水合物识别中的应用[J].海洋地质前沿,2018,34(7):46-55.
MENG Dajiang, WEN Pengfei, ZHANG Xudong. Application of AVO inversion to gas hydrates identification to the Qiongdongnan area, Northern south China sea[J]. Marine Geology Frontiers, 2018, 34(7): 46-55.

[23] 裴建新,袁翔,罗鸣,等.CMP域内海洋CSEM法探测海底天然气水合物分辨能力研究[J].中国海洋大学学报(自然科学版),2019,49(6):72-78.
PEI Jianxin, YUAN Xiang, LUO Ming, et al. Research on resolution of marine CSEM method in CMP domain[J]. Periodical of Ocean University of China, 2019, 49(6): 72-78.

[24] 薛花,杜民,文鹏飞,等.南海神狐海域试采区天然气水合物精细速度建模方法[J].海洋地质前沿,2019,35(7):8-17.
XUE Hua, DU Min, WEN Pengfei, et al. Research and application of fine velocity modeling to gas hydrate testing development in the Shenhu area of south China sea[J]. Marine Geology Frontiers, 2019, 35(7): 8-17.

[25] 景建恩,伍忠良,邓明,等.南海天然气水合物远景区海洋可控源电磁探测试验[J].地球物理学报,2016,59(7):2564-2572.
JING Jianen, WU Zhongliang, DENG Ming, et al. Experiment of marine controlled-source electromagnetic detection in a gas hydrate prospective region of the South China Sea[J]. Chinese Journal of Geophysics, 2016, 59(7): 2564-2572.

[26] 李延,文鹏飞,张宝金,等.频率衰减梯度属性在南海北部神狐海域天然气水合物检测中的应用[J].海洋地质前沿,2019,35(7):1-7.
LI Yan, WEN Pengfei, ZHANG Baojin, et al. Application of frequency attenuation gradient to gas hydrate prediction: A case from Shenhu area, northern south China sea[J]. Marine Geology

Frontiers, 2019, 35(7): 1-7.

[27] 孟大江,文鹏飞,张宝金,等.天然气水合物储层反演及饱和度预测[J].海洋地质前沿,2019,35(11):43-51.
MENG Dajiang, WEN Pengfei, ZHANG Baojin, et al. Gas hydrate reservoir inversion and saturation prediction[J]. Marine Geology Frontiers, 2019, 35(11): 43-51.

[28] 黄天佳,李小森,张郁,等.海洋天然气水合物地层钻井安全问题研究进展[J].新能源进展,2019,7(6):513-521.
HUANG Tianjia, LI Xiaosen, ZHANG Yu, et al. Research progress of the safety issues of marine natural gas hydrate reservoirs drilling[J]. Advances in New and Renewable Energy, 2019, 7(6): 513-521.

[29] 尉建功,杨胜雄,梁金强,等.海洋钻探对甲烷渗漏的影响:以南海北部天然气水合物钻探GMGS2_16站位为例[J].海洋地质与第四纪地质,2018,38(5):63-70.
WEI Jiangong, YANG Shengxiong, LIANG Jinqiang, et al. Impact of seafloor drilling on methane seepage—enlightenments from natural gas hydrate drilling site GMGS2-16, northern South China Sea[J]. Marine Geology & Quaternary Geology, 2018, 38(5): 63-70.

[30] 蒋善良,陈超,利观宝,等.盐含量对天然气水合物防聚剂性能的影响[J].天然气工业,2019,39(8):120-125.
JIANG Shanliang, CHEN Chao, LI Guanbao, et al. Effect of salt contents on the gas hydrate anti-agglomerant performance[J]. Natural Gas Industry, 2019, 39(8): 120-125.

[31] 黄芳飞,张旗,何涛,等.海域天然气水合物监测井技术进展与挑战[J].科学技术与工程,2019,19(27):21-30.
HUANG Fangfei, ZHANG Qi, HE Tao, et al. Technological progresses and challenges of marine natural gas hydrate monitoring well[J]. Science Technology and Engineering, 2019, 19(27): 21-30.

[32] 陈玉凤,梁德青,吴能友.南海神狐海域水合物对岩心电阻率的影响[J].石油地球物理勘探,2018,53(6):1241-1246.
CHEN Yufeng, LIANG Deqing, WU Nengyou. Resistivity characteristics of core samples containing natural gas hydrates in Shenhu Area, the South China Sea[J]. Oil Geophysical Prospecting, 2018, 53(6): 1241-1246.

[33] 康冬菊,梁金强,匡增桂,等.元素俘获能谱测井在神狐海域天然气水合物储层评价中的应用[J].天然气工业,2018,38(12):54-60.
KANG Dongju, LIANG Jinqiang, KUANG Zenggui, et al. Application of elemental capture spectroscopy logging in hydrate reservoir evaluation in the Shenhu sea area[J]. Natural Gas Industry, 2018, 38(12): 54-60.

[34] 张怀文,程远方,李梦来,等.南海北部深水浅层天然气水合物储层力学特性试验及强度准则建立[J].中国海上油气,2017,29(6):115-121.
ZHANG Huaiwen, CHENG Yuanfang, LI Menglai, et al. Tests on rock mechanics and establishment of strength criterion for gas hydrate reservoirs in the northern shallow sediments of South China Sea[J]. China Offshore Oil and Gas, 2017, 29(6): 115-121.

[35] 石思思,陈星州,马健,等.南海北部神狐海域W19井天然气水合物储层类型与特征[J].特种油气藏,2019,26(3):24-29.
SHI Sisi, CHEN Xingzhou, MA Jian, et al. Natural gas hydrate reservoir classification and characterization in the Well W19 of Shenhu Sea Area, northern South China Sea[J]. Special Oil & Gas Reservoirs, 2019, 26(3):24-29.

[36] 邓义楠,方允鑫,张欣,等.南海琼东南海域沉积物的微量元素地球化学特征及其对天然气水合物的指示意义[J].海洋地质与第四纪地质,2017,37(5):70-81.
DENG Yinan, FANG Yunxin, ZHANG Xin, et al. Trace element geochemistry of sediments in Qiongdongnan area, the south China sea, and its implications for gas hydrates[J]. Marine Geology & Quaternary Geology, 2017, 37(5): 70-81.

[37] 陈琳莹,罗敏.南海西沙西南海底麻坑区天然气水合物发育的孔隙水地球化学证据[J].地球化学,2017,46(6):557-566.
CHEN Linying, LUO Min. Gas hydrate occurrences inferred from pore water geochemistry in the pockmark field in the southwestern Xisha uplift, south China sea[J]. Geochemical, 2017, 46(6): 557-566.

[38] 杜炳锐,白大为,裴发根,等.水合物沉积物介电特性测量实验[J].石油地球物理勘探,2019,54(1):118-126.
DU Bingrui, BAI Dawei, PEI Fagen, et al. An experimental study on dielectric properties of hydrate sediments in radar wave propagation[J]. Oil Geophysical Prospecting, 2019, 54(1): 118-126.

[39] 彭力,宁伏龙,李维,等.用原子力显微镜研究温度和接触界面对THF水合物形貌的影响[J].中国科学:物理学 力学 天文学,2019,49(3):144-152.
PENG Li, NING Fulong, LI Wei, et al. Investigation on the effect of growth temperature and contact interface on surface characteristics of THF clathrate hydrates by atomic force microscopy[J]. Scientia Sinica (Physica, Mechanica & Astronomica), 2019, 49(3): 144-152.

[40] 鲁晓兵,张旭辉,王淑云.天然气水合物开采相关的安全性研究进展[J].中国科学:物理学 力学 天文学,2019,49(3):7-37.
LU Xiaobing, ZHANG Xuhui, WANG Shuyun. Advances on the safety related with natural gas hydrate exploitation[J]. Scientia Sinica(Physica, Mechanica & Astronomica), 2019, 49(3): 7-37.

[41] 李守定,孙一鸣,陈卫昌,等.天然气水合物开采方法及海域试采分析[J].工程地质学报,2019,27(1):55-68.
LI Shouding, SUN Yiming, CHEN Weichang, et al. Analyses of gas production methods and offshore production tests of natural gas hydrates[J]. Journal of Engineering Geology, 2019, 27(1): 55-68.

[42] 蒲子芳,孙伟博,张大明,等.天然气水合物开采过程中的风险与防控[J].海洋工程装备与技术,2019,6(S1):474-477.
PU Zifang, SUN Weibo, ZHANG Daming, et al. Risks and prevention measures in the process of natural gas hydrate exploitation[J]. Ocean Engineering Equipment and Technology, 2019, 6(S1): 474-477.

[43] 刘康,朱渊,陈国明,等.天然气水合物开采井筒温度监测实验[J].实验室研究与探索,2019,38(10):76-79.

LIU Kang, ZHU Yuan, CHEN Guoming, et al. Experimental study on wellbore monitoring of methane hydrate[J]. Research and Exploration in Laboratory, 2019, 38(10): 76-79.

[44] 刘金龙,王淑红,OBEYSEKARA Asiri,等.天然气水合物稳定带内流体压裂计算的程序耦合方法[J].热带海洋学报,2020,39(1):94-105.
LIU Jinlong, WANG Shuhong, OBEYSEKARA Asiri, et al. Codes coupling method for simulating hydraulic fracturing within the gas hydrate stability zone[J]. Journal of Tropical Oceanography, 2020, 39(1): 94-105.

[45] 康家浩,郭威,陆程,等.水合物开采过程中影响套管式加热器对井周地层加热效果的数值模拟[J].探矿工程(岩土钻掘工程),2019,46(6):1-7.
KANG Jiahao, GUO Wei, LU Cheng, et al. Numerical simulation of heating process of casing heater in natural gas hydrate production wells[J]. Exploration Engineering (Rock & Soil Drilling and Tunneling), 2019, 46(6): 1-7.

[46] 黄芳飞,张鑫,陆红锋,等.天然气水合物储层光电温压监测技术探秘[J].国土资源科普与文化,2019(2):25-27.
HUANG Fangfei, ZHANG Xin, LU Hongfeng, et al. Exploration of photoelectric temperature and pressure monitoring technology for natural gas hydrate reservoir[J]. Scientific and Cultural Popularization of Land and Resources, 2019(2): 25-27.

[47] 孙春岩,王栋琳,张仕强,等.深海甲烷电化学原位长期监测技术及其在海洋环境调查和天然气水合物勘探中的意义[J].物探与化探,2019,43(1):1-16.
SUN Chunyan, WANG Donglin, ZHANG Shiqiang, et al. Deep sea methane electrochemical in- situ long- term monitoring technology and its significance in the ocean environmental investigation and gas hydrate exploration[J]. Geophysical and Geochemical Exploration, 2019, 43(1): 1-16.

[48] 邱顺佐,王国荣,周守为,等.海底天然气水合物原位提纯分离器结构设计及优选[J].中国海上油气,2019,31(2):125-131.
QIU Shunzuo, WANG Guorong, ZHOU Shouwei, et al. Structural design and optimization of in- situ purification separator for submarine gas hydrate[J]. China Offshore Oil and Gas, 2019, 31(2): 125-131.

[49] 刘以宣,詹文欢.南海变质基底基本轮廓及其构造演化[J].安徽地质,1994(Z1):82-90.
LIU Yixuan, ZHAN Wenhuan. BASIC Outline and tectonic evolution of the metamorphic BASEMENT in the south China sea[J]. Geology of Anhui, 1994(Z1): 82-90.

[50] 张功成,贾庆军,王万银,等.南海构造格局及其演化[J].地球物理学报,2018,61(10):4194-4215.
ZHANG Gongcheng, JIA Qingjun, WANG Wanyin, et al. On tectonic framework and evolution of the South China Sea[J]. Chinese Journal of Geophysics, 2018, 61(10): 4194-4215.

[51] 蔡东升,冯晓杰,高乐,等.中国近海前第三纪残余盆地及其勘探潜力与方向[J].中国海上油气,2004(1):3-19.
CAI Dongsheng, FENG Xiaojie, GAO Le, et al. Pretertiary residual basins off the coast of China and their exploration potential and direction[J]. China Offshore Oil and Gas, 2004 (1): 3-19.

[52] 张厚和,刘鹏,廖宗宝,等.南沙海域主要盆地地质特征与油气分布[J].中国石油勘探,2018,23(1):62-70.
ZHANG Houhe, LIU Peng, LIAO Zongbao, et al. Geological characteristics and hydrocarbon distribution in major sedimentary basins in Nansha sea areas[J]. China Petroleum Exploration, 2018, 23(1): 62-70.

[53] 何家雄,夏斌,张启明,等.南海北部边缘盆地生物气和亚生物气资源潜力与勘探前景分析[J].天然气地球科学,2005,16(2):167-174.
HE Jiaxiong, XIA Bin, ZHANG Qiming, et al. Analysis of biogas and sub biogas resource potential and exploration prospect in the northern margin basin of the South China Sea[J]. Natural Gas Geoscience, 2005, 16(2): 167-174.

[54] 李鹏春,赵中贤,张翠梅,等.南沙海域礼乐盆地沉积过程和演化[J].地球科学(中国地质大学学报),2011,36(5):837-844.
LI Pengchun, ZHAO Zhongxian, ZHANG Cuimei, et al. Depositional process and evolution of Liyue Basin in Southern South China Sea[J]. Geoscience (Journal of China University of Geosciences), 2011, 36(5): 837-844.

[55] 刘宝明,夏斌,刘振湖,等.南海西南部海区油气富集成藏类型分析[J].石油实验地质,2002,24(4):322-326.
LIU Baoming, XIA Bin, LIU Zhenhu, et al. Analysis of hydrocarbon accumulation types in the southwestern South China Sea[J]. Petroleum Geology & Experiment , 2002, 24(4): 322-326.

[56] 梁建设,张功成,王璞珺,等.南海陆缘盆地构造演化与烃源岩特征[J].吉林大学学报(地球科学版),2013,43(5):1309-1319.
LIANG Jianshe, ZHANG Gongcheng, WANG Pujun, et al. Tectonic evolution of epicontinental basins in South China Sea and their feature of source rocks[J]. Journal of Jilin University (Earth Science Edition), 2013, 43(5): 1309-1319.

[57] 梁金强,张光学,陆敬安,等.南海东北部陆坡天然气水合物富集特征及成因模式[J].天然气工业,2016,36(10):157-162.
LIANG Jinqiang, ZHANG Guangxue, LU Jingan, et al. Accumulation characteristics and genetic models of natural gas hydrate reservoirs in the NE slope of the South China Sea[J]. Natural Gas Industry, 2016, 36(10): 157-162.

[58] 刘宝明,金庆焕.南沙西南海域万安盆地油气地质条件及其油气分布特征[J].世界地质,1996,15(4):35-41.
LIU Baoming, JIN Qinghuan. Hydrocarbon geological conditions and distribution characters of Wan'an Basin in the Southwestern South China Sea[J]. World Geology, 1996, 15(4): 35-41.

[59] 魏伟,张金华,吝文,等.天然气水合物成藏机理及主控因素[J].新疆石油地质,2010,31(6):563-566.
WEI Wei, ZHANG Jinhua, LIN Wen, et al. Mechanism and controlling factors of natural gas hydrate accumulation[J]. XinJiang Petroleum Geology, 2010, 31(6): 563-566.

(编辑 李颖洁)