文章编号:1001-6112(2023)02-0203-07
doi:10.11781/sysydz202302203

深层—超深层油气成藏研究新进展及展望

关晓东[1],郭　磊[2]
1. 中国石化 科技部,北京　100020;
2. 中国石油 冀东油田分公司,河北 唐山　063000

摘要:我国深层—超深层油气资源丰富,但勘探程度较低。深层—超深层具有比浅层更高的温度和压力,并且来自于深部的流体在深层的作用更强,因此,深层—超深层油气藏与浅层油气藏具有不同的成藏机理。通过广泛调研国内外相关研究,较为系统地总结了深层—超深层油气藏在成烃、成储和成藏方面的特殊性及其主控因素。提出深层—超深层环境中存在促进烃源灶继续生烃的物质和能量,能进一步促进油气形成;起源于深层—超深层储层之下的流体可以发挥建设性作用,从而在深层形成优质规模储层;流经烃源岩和储层的深部富 CO_2 流体对深层烃类具有促排作用,并在浅层发挥促藏作用。尽管前人归纳的这些理论对指导发现规模油气藏尚存一些争议,但应该看到,在深层—超深层独特的地质条件下,在总结油气成藏规律时,全面、充分考虑各种因素,有助于提高深层—超深层探井成功率,降低勘探成本。

关键词:深层;超深层;富 CO_2 流体;油气成藏
中图分类号:TE122.3　　　**文献标识码**:A

New progress and prospect of oil and gas accumulation research in deep to ultra-deep strata

GUAN Xiaodong[1], GUO Lei[2]
1. *Department of Science and Technology Development*, *SINOPEC*, *Beijing* 100020, *China*;
2. *Jidong Oilfield Company*, *CNPC*, *Tangshan*, *Heibei* 063000, *China*

Abstract: There are abundant deep to ultra-deep oil and gas resources in China, but the degree of exploration is low. The deep to ultra-deep reservoirs have higher temperature and pressure than the shallow ones, and the fluid from the deep strata plays a stronger role in the deep formations. Therefore, the deep to ultra-deep reservoirs have different accumulation mechanism from the shallow ones. Through extensive research at home and abroad, the particularity and main control factors of hydrocarbon generation, reservoir-forming and hydrocarbon accumulation of deep to ultra-deep oil and gas reservoirs were systematically summarized. It was suggested that there are materials and energy in the deep to ultra-deep environment that can promote the continuous hydrocarbon generation of hydrocarbon kitchens, which can further promote oil and gas accumulation. Fluids originating from deep to ultra-deep reservoirs can play a constructive role in forming high-quality large-scale reservoirs in deep strata. The deep CO_2-rich fluid flowing through source rocks and reservoirs can promote the hydrocarbon expulsion in deep strata and the hydrocarbon accumulation in shallow strata. Although these theories summarized by predecessors are still controversial in guiding the discovery of large-scale oil and gas reservoirs, it should be seen that under the unique geological conditions of deep to ultra-deep strata, when summarizing the law of oil and gas accumulation, comprehensive and full consideration of various factors will help to improve the success rate of deep to ultra-deep exploration wells and reduce exploration costs.

Key words: deep strata; ultra-deep strata; CO_2-rich fluid; oil and gas accumulation

全球范围内,埋深 4 500 m 一般是深层与浅层的分界深度。2005 年,全国矿产储量委员会根据我国油气勘探实践,将埋深处于 3 500~4 500 m 的地层称为深层,而大于 4 500 m 的地层称为超深层[1]。随着油气勘探不断向深层推进,并根据中国东、西部地温场特点,目前在我国东部地区,埋深 3 500~4 500 m 为深层领域;而埋深 4 500~6 000 m 则为西部深层领域。东部埋深超过4 500 m,西部

收稿日期:2022-10-11;**修订日期**:2023-02-23。
作者简介:关晓东(1968—),男,高级工程师,从事油气勘探研究及科技管理。E-mail:guanxd@sinopec.com。
基金项目:国家自然科学基金(U20B6001,42172168)联合资助。

超过6 000 m的地层,则为超深层领域。特别是我国西部地区超深层领域,近年来不断取得油气勘探突破,已经成为我国油气增储上产的主要领域。塔里木盆地近年来在埋深大于7 000 m的超深层,发现了顺北—富满等资源规模超10亿吨的巨型油气区,进一步表明我国深层—超深层油气勘探具有广阔的前景[2-3]。

深层—超深层具有与浅层显著不同的温度、压力环境,并且在深层—超深层地层更接近沉积盆地基底,基底之下的物质和能量对深部地层的影响更加明显[4]。这种环境下,深层—超深层油气形成过程与浅层是否有明显的不同?哪些因素影响深层—超深层油气形成过程?其影响过程与机理如何?对这些问题的深入研究,是完善油气基础理论、进一步提升勘探效率的必由之路。

本文在对深层—超深层油气成藏过程及机理进行系统调研的基础上,对深层—超深层油气形成过程的关键理论问题进行了深入分析,以期为深层—超深层油气勘探提供新思路。

1 油气形成研究理论新进展

传统的石油地质学理论认为,干酪根生产石油所需的物质,绝大部分来源于干酪根本身,并且随着生烃反应的推进,后期以生产天然气为主(图1)[5]。

随着技术的进步,可以在实验室内模拟自然界中油气的形成过程,不断推动石油地质理论的发展。LEWAN等较早地认识到封闭模拟实验系统中加入水之后,实验产物与天然原油更相似[6],从而认为水参与了有机质生烃的过程[7]。

尽管这个观点引起了一些争议[8-9],但文章提出的向密闭热解生烃实验系统中加入水的方法,目前已成为生烃模拟实验的主流方法[10-12]。这在事实上改变了传统石油地质学认为的“生成油气的物质绝大部分来自有机质本身”的认识,认为有机质之外的无机物对有机质生烃过程有具体的物质贡献。前人开展的富氢岩石促进有机质生烃的实验[13],将有机质之外的含氢物质由水拓展到橄榄岩等富氢岩石。金之钧等[14]通过模拟实验证实,深部流体向含油气盆地内输入的氢气可以提高液态烃产率,开辟了一种新的有机质外含氢物质——氢气促进有机质生烃,特别是液态烃的研究,并认为存在有机—无机复合成因油气。前人论证了水提供的氢和氧原子参与了有机质的裂解过程,定性描述了水参与有机质生烃的化学反应类型及过程,

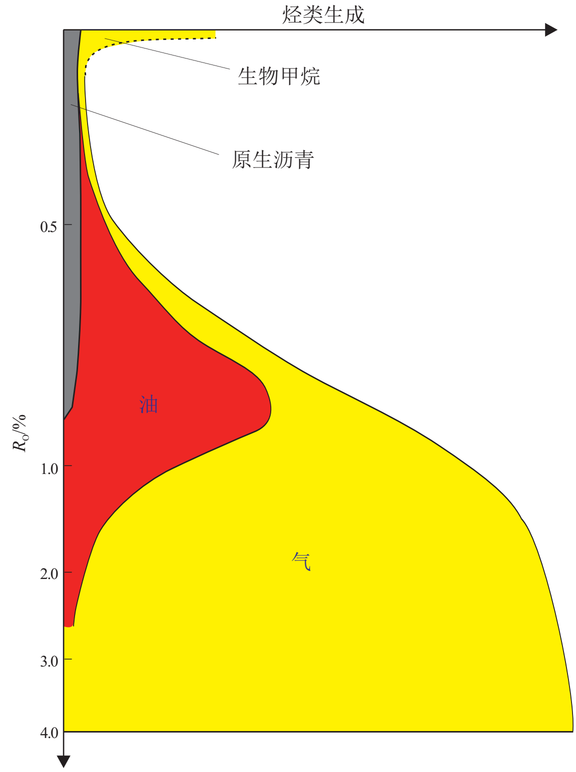

图1 传统的干酪根生烃模式

据参考文献[5]修改。

Fig.1 Traditional hydrocarbon generation model of kerogen

明确提出了石油形成的过程中存在“有机—无机相互作用”,建立了新的烃类生成与埋藏深度(时间)关系模式(图2)[15]。

与传统模式(图1)不同,SEEWALD等[15]认为在没有外源氢的条件下,在生烃高峰之后,有机质生油和生气能力会逐渐降低(图2a);但加入水作为外源氢之后,在生烃高峰之后,有机质生气能力持续增强,CO_2和有机酸产率也逐渐增加(图2b)。

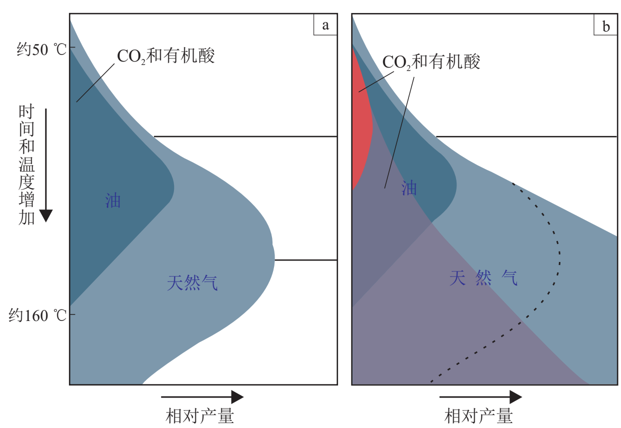

图2 外源氢参与下有机质生烃模式(b)与传统生烃模式(a)的异同

据参考文献[15]修改。

Fig.2 Differences and similarities between organic matter hydrocarbon generation model with the participation of exogenous hydrogen (b) and traditional hydrocarbon generation model (a)

《Science》持续发表的研究成果表明,幔源岩石中存在大量的水[16-18],进一步证明在地质条件下,水促进有机质生烃过程是真实存在的。

HE 等利用封闭热解生烃模拟实验系统,开展了烃源岩加水热解生烃实验,基于碳氢同位素组成变化特征,认为加入水之后,甲烷中的氢元素有20%来自于加入的水,提出了深层天然气加氢生气的新模式(图 3)[19]。

一般而言,深层烃源岩具有时代老、成熟度高的特点。这些烃源岩在深层环境下是否具有生烃能力,对于准确评估深层—超深层油气资源量具有重要意义。HUANG 等利用塔里木盆地玉尔吐斯组[20]和延怀盆地下马岭组低熟烃源岩[21],开展了不同成熟度烃源岩在催化条件下加氢生烃的模拟实验,并基于产物的碳同位素组成特征,认为不但高成熟烃源岩在存在外源氢(氢气)和催化剂的条件下可以继续生成甲烷,同时,不同成熟度的干酪根在生烃阶段产生的 CO_2 可以与 H_2 通过费托合成生成甲烷。因此,外源氢的加入,一方面可以促进烃源岩,特别是高成熟烃源岩生成烃类物质;另一方面,充足的外源氢可以使封闭系统中有机质生烃过程中产生的 CO_2 转化为甲烷。这一生烃过程的确立,对于深层页岩油气勘探具有深远意义,因为页岩油气是以烃源岩自生自储为主的封闭成藏系统,系统中的含氢物质一方面可以促进有机质生烃,另一方面 CO_2 转化为 CH_4,造成甲烷碳同位素组成特别复杂化,从而影响对页岩气甲烷碳同位素组成特征的评估与应用。

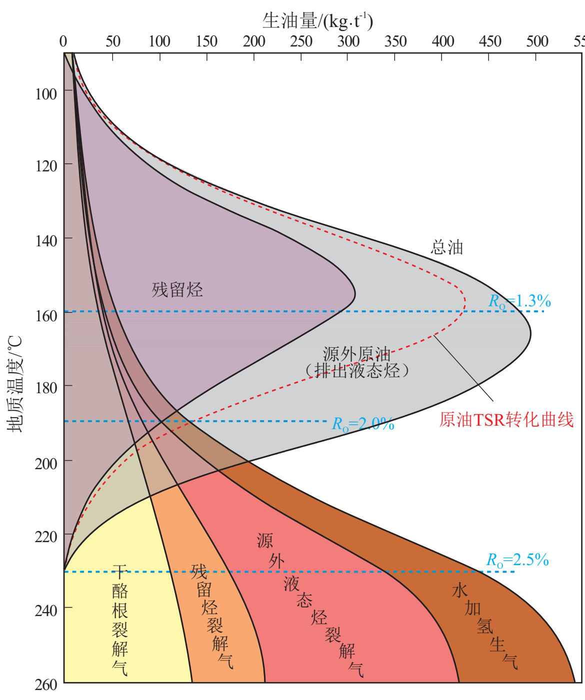

图 3　外源氢作用下烃源岩生烃新模式

据参考文献[19]修改。

Fig.3　A new hydrocarbon generation model of source rocks under the action of exogenous hydrogen

在上述研究中,沉积盆地,特别是深层条件下氢气的供应状况,成为制约地质条件下烃源岩能否加氢生烃的关键要素。研究表明,在发育深部流体活动的沉积盆地中,氢气可以广泛分布[22],并且在板块碰撞带周边的构造活跃区存在高含量氢气[23]。因此,在地质条件下,存在较为充足的氢气参与有机质生烃过程。

2　深层储集空间理论研究新进展

目前,全球范围内的油气勘探都在向深层及超深层发展。国外正在生产的埋深大于 5 000 m 的 32 个碳酸盐岩油气田主要分布在北美、俄罗斯、意大利等地区,最深的是位于美国西内盆地阿纳达科凹陷的米尔斯兰奇奥陶系气田,埋深 7 663~8 083 m[24]。我国在西部塔里木盆地[25-26]、四川盆地[27]均发现了深层碳酸盐岩油气藏。我国东部盆地中也发现了超深层的碳酸盐岩油气藏[28]。

传统理论认为,碳酸盐岩储层内的储集空间,即孔隙度,随着储层的埋深逐渐减低[29],但上述勘探实践表明,在盆地的深层可以发育优质储层。塔里木盆地塔深 1 井白云岩埋深 7 135 m 时的孔隙度为 1.0%,随着埋深的增大,孔隙度逐渐增大到 8 408 m的 9.1%。前人研究表明,碳酸盐岩储层在深部热液流体影响下经重结晶[30]、溶蚀改造[31]后,可以形成优质储层。这类优质储层的发育,受动力学与热力学因素控制[32-35],并在深部流体发育的地区广泛分布(图 4)[36]。

深层碳酸盐岩储层发育机理研究得到了前人的充分重视,提出了深埋溶蚀[37]、准同生期渗透回流[38]等深部储层的成因机制,但深层碎屑岩的发育机理研究不多。我国东部裂谷盆地深部碎屑岩储层中多次报道过片钠铝石的存在[39-41],一般认为是碎屑岩中的长石矿物与 CO_2 发生反应形成的蚀变矿物,并以此作为判识深部流体活动的标志之一[42]。

综上所述,在深层油气储集空间研究方面,碳酸盐岩储层在热液流体影响下的改造过程,已经得到了较为广泛的关注,但对于热液流体活动对碎屑岩储层发育机制的研究,仍较为薄弱,缺乏进一步的实验研究与更深入的地质研究。

3　深层油气成藏理论研究新进展

CO_2 的临界温度和压力分别为30.98 ℃和

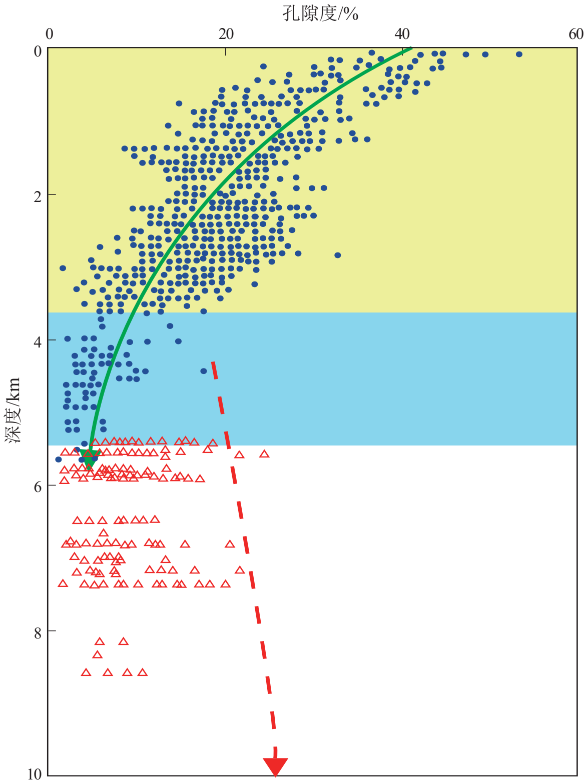

图 4 沉积盆地基底之下的流体影响储层孔隙度演化

据参考文献[36]修改。

Fig.4 Fluid under the basement of sedimentary basin affects the evolution of reservoir porosity

7.38 MPa[43]，对于深部富含 CO_2 流体而言，CO_2 多处于超临界状态，密度接近于液体，对有机物质的溶解能力非常强[44]，这一特性已广泛应用于植物油提取[45-46]、高分子聚合物处理[47]、制药等有机处理领域[48]。前人利用超临界 CO_2 抽提油页岩的研究分子标志物[49]的实验表明，超临界 CO_2 流体可以更加高效、准确地提取烃类的地球化学特征。在压力低于 20 MPa 时，CO_2 中主要萃取溶解 C_{20} 以下组分；随着压力的增加，剩余重质组分逐渐开始溶解[50]。

在地质条件下，按照静水和静岩压力梯度分别为 10 MPa/km 和 26 MPa/km 以及 20 °C/km 的地温梯度来算，CO_2 在几百米埋深就处于超临界状态。对油气来说，超临界态的 CO_2 是一种非常好的溶剂[51]，能溶解油气并向浅部地层运移，极大地降低了油气运移阻力[52]；此外，深部流体较高的温度也能显著降低原油黏度，有利于油气在富水地层中的传输运移。在澳大利亚塔斯马尼亚岛锡钨矿中发现了 CO_2—水—重烃共存的包裹体，包裹体均一温度在 300～450 ℃之间，并认为 CO_2 有岩浆来源与非岩浆来源的混合成因[53]；而在加拿大埃利奥特湖 2 450 Ma 的石英砂岩中也发现了无机成因 CO_2、水、气态烃和液态烃共存的流体包裹体，其均一温度为 250～330 ℃[54]。这些发现证实了富 CO_2 流体与油气之间存在强烈的相互作用，因此深部热液活动能促使油气向浅部运移成藏[55]。

我国下扬子黄桥地区浅层油气储层 CO_2 与原油共生包裹体等现象表明，深层栖霞组烃源岩中的滞留烃被向上运移的深源 CO_2 萃取，并共同运移至浅部成藏，巴西桑托斯盆地[56]和我国南海[57]等都存在类似现象，因此，在深部富 CO_2 流体作用下存在原油—CO_2 耦合成藏模式(图5)[53,58]。因此推测

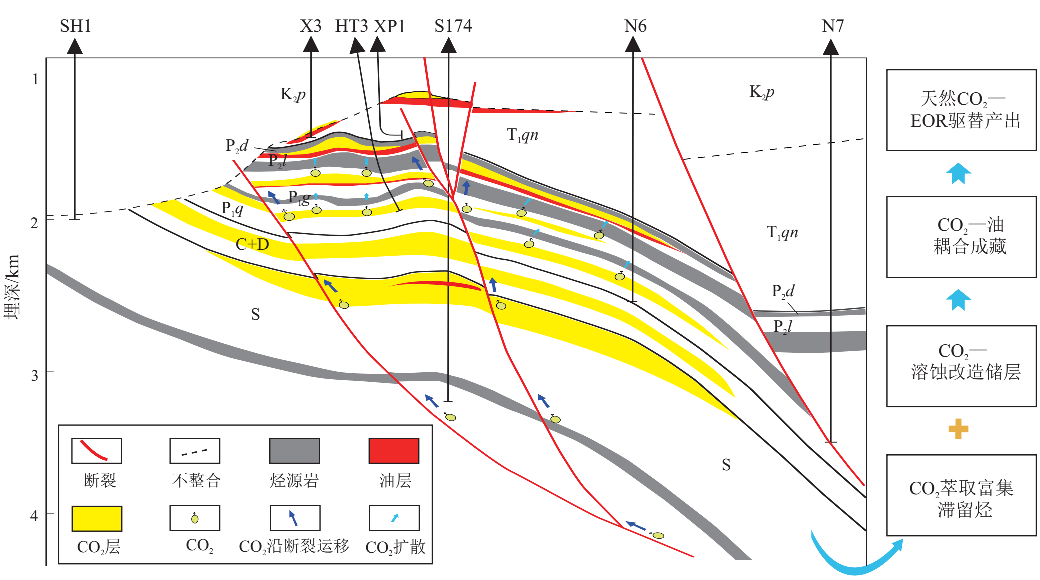

图 5 深源 CO_2—原油耦合成藏模式

据参考文献[53]修改。

Fig.5 Deep source CO_2 and crude oil coupling reservoir formation model

下扬子地区深部二叠系是深层油气勘探主要领域,由此丰富和完善了深层油气成藏模式。

不可否认的是,CO_2—原油耦合成藏模式的规模和发育环境有待进一步深入研究。但另一方面,随着油气勘探向深部推进,勘探成本将越来越高。因此,需要综合吸收各方面的研究成果,全面认识深层油气成藏全过程,厘清不同地质条件下影响油气成藏要素的过程及机理,才能更加准确地重建深层油气成藏过程,提高油气分布预测的成功率,进而提高深层油气勘探探井的成功率,降低勘探成本。

4　结论

(1)我国深层油气资源潜力大,探明率低,但已经获得一些重要突破。因此,深层油气勘探开发是保障我国能源安全的重要接替领域。由于深层具有异常高的温度和压力,并且更容易受到来自盆地基底之下的流体的影响,因此具有不同的油气成藏条件。

(2)深部地质条件下,生烃母质在高温及源外含氢或富氢物质的影响下,可以显著提高生烃率,并且形成有机—无机复合成因的烃类。但是,这种生烃模式的规模有多大,产物如何识别,仍需要深入研究。

(3)深部储层,特别是碳酸盐岩储层或者碎屑岩储层中的碳酸盐胶结物,对深源富 CO_2 较为敏感。在富 CO_2 流体作用下,深层碳酸盐岩储层或胶结物可以在深部被溶解,并随流体运移至其他位置。这些被溶蚀的碳酸盐岩或胶结物的位置,成为深层优质储集空间,并在一定条件下可以形成规模优质储层。

(4)深源富 CO_2 流体对烃源岩或致密储层中的烃类具有较强的萃取作用,并且可以随富 CO_2 流体运移至浅部成藏,特别是轻质油更容易从深部长距离运移至浅部成藏,此即 CO_2—原油耦合成藏新模式。

(5)深层高温高压、环境复杂的地质特点决定了深层油气成藏过程有其独特的复杂性,因此,要综合考虑影响深层油气成藏的各种因素,充分吸收各方面的研究成果,才能进一步提升对深层油气成藏过程的认识,提高探井成功率,降低勘探成本。

参考文献:

[1]　何治亮,马永生,朱东亚,等.深层—超深层碳酸盐岩储层理论技术进展与攻关方向[J].石油与天然气地质,2021,42(3):533-546.

HE Zhiliang,MA Yongsheng,ZHU Dongya,et al. Theoretical and technological progress and research direction of deep and ultra-deep carbonate reservoirs[J]. Oil & Gas Geology,2021,42(3):533-546.

[2]　云露,邓尚.塔里木盆地深层走滑断裂差异变形与控储控藏特征:以顺北油气田为例[J].石油学报,2022,43(6):770-787.

YUN Lu,DENG Shang.Structural styles of deep strike-slip faults in Tarim Basin and the characteristics of their control on reservoir formation and hydrocarbon accumulation:a case study of Shunbei oil and gas field[J].Acta Petrolei Sinica,2022,43(6):770-787.

[3]　杨海军,陈永权,田军,等.塔里木盆地轮探 1 井超深层油气勘探重大发现与意义[J].中国石油勘探,2020,25(2):62-72.

YANG Haijun,CHEN Yongquan,TIAN Jun,et al.Great discovery and its significance of ultra-deep oil and gas exploration in well Luntan-1 of the Tarim Basin[J].China Petroleum Exploration,2020,25(2):62-72.

[4]　金之钧,胡文瑄,张刘平,等.深部流体活动及油气成藏效应[M].北京:科学出版社,2007:66-76.

JIN Zhijun,HU Wenxuan,ZHANG Liuping,et al.Deep fluid activity and hydrocarbon accumulation effect[M].Beijing:Science Press,2007:66-76.

[5]　TISSOT B P,WELTE D H.Petroleum formation and occurrence[M].2nd ed.New York:Springer-Verlag,1984.

[6]　LEWAN M D,WINTERS J C,MCDONALD J H.Generation of oil-like pyrolyzates from organic-rich shales[J].Science,1979,203(4383):897-899.

[7]　LEWAN M D.Experiments on the role of water in petroleum formation[J].Geochimica et Cosmochimica Acta,1997,61(17):3691-3723.

[8]　BURNHAM A.Comments on "Experiments on the role of water in petroleum formation" by M. D. Lewan[J]. Geochim et Cosmochimica Acta,1998,62:2209-2212.

[9]　LEWAN M D.Reply to the comment by A. K. Burnham on "Experiments on the role of water in petroleum formation"[J]. Geochimica et Cosmochimica Acta,1998,62:2211-2216.

[10]　ZHOU Jianwei,LI Shuyuan,ZHONG Ningning.Study on hydropyrolysis of sedimentary organic matter and geochemical information of hydropyrolysates[J].Journal of Fuel Chemistry and Technology,2007,35(6):648-654.

[11]　WU Liangliang,LIAO Yuhong,FANG Yunxin,et al.The comparison of biomarkers released by hydropyrolysis and Soxhlet extraction from source rocks of different maturities[J]. Chinese Science Bulletin,2013,58(3):373-383.

[12]　FERNANDO F L P. Recent advances on fast hydropyrolysis of biomass[J].Catalysis Today,2016,269:148-155.

[13]　JIN Qiang,XIONG Shousheng,LU Peide. Catalysis and hydrogenation:volcanic activity and hydrocarbon generation in rift basins,Eastern China[J].Applied Geochemistry,1999,14(5):547-558.

[14]　金之钧,张刘平,杨雷,等.沉积盆地深部流体的地球化学特征及油气成藏效应初探[J].地球科学,2002,27(6):659-665.

JIN Zhijun,ZHANG Liuping,YANG Lei,et al.Primary study of geochemical features of deep fluids and their effectiveness on oil/gas reservoir formation in sedimental basins [J]. Earth Science, 2002, 27(6): 659-665.

[15] SEEWALD J S. Organic-inorganic interactions in petroleum-producing sedimentary basins[J]. Nature, 2003, 426(6964): 327-333.

[16] BELL D R, ROSSMAN G R. Water in Earth's mantle: the role of nominally anhydrous minerals [J]. Science, 1992, 255(5050): 1391-1397.

[17] MURAKAMI M, HIROSE K, YURIMOTO H, et al. Water in Earth's lower mantle [J]. Science, 2002, 295(5561): 1885-1887.

[18] HALLIS L J, HUSS G R, NAGASHIMA K, et al. Evidence for primordial water in Earth's deep mantle[J]. Science, 2015, 350(6262): 795-797.

[19] HE Kun, ZHANG Shuichang, MI Jingkui, et al. Carbon and hydrogen isotope fractionation for methane from non-isothermal pyrolysis of oil in anhydrous and hydrothermal conditions[J]. Energy Exploration & Exploitation, 2019, 37(5): 1558-1576.

[20] HUANG Xiaowei, JIN Zhijun, LIU Quanyou, et al. Geochemical characteristics of catalytic hydrogenation of low-mature kerogen under deep fluids[J]. Frontiers in Earth Science, 2022, 10: 885860.

[21] HUANG Xiaowei, JIN Zhijun, LIU Quanyou, et al. Catalytic hydrogenation of post-mature hydrocarbon source rocks under deep-derived fluids: an example of Early Cambrian Yurtus Formation, Tarim Basin, NW China[J]. Frontiers in Earth Science, 2021, 9: 626111.

[22] 孟庆强.地质体中天然氢气成因识别方法初探[J].石油实验地质,2022,44(3):552-558.
MENG Qingqiang. Identification method for the origin of natural hydrogen gas in geological bodies[J]. Petroleum Geology & Experiment, 2022, 44(3): 552-558.

[23] 孟庆强,金之钧,孙冬胜,等.高含量氢气赋存的地质背景及勘探前景[J].石油实验地质,2021,43(2):208-216.
MENG Qingqiang, JIN Zhijun, SUN Dongsheng, et al. Geological background and exploration prospects for the occurrence of high-content hydrogen[J]. Petroleum Geology & Experiment, 2021, 43(2): 208-216.

[24] 马永生,蔡勋育,赵培荣.深层、超深层碳酸盐岩油气储层形成机理研究综述[J].地学前缘,2011,18(4):181-192.
MA Yongsheng, CAI Xunyu, ZHAO Peirong. The research status and advances in porosity evolution and diagenesis of deep carbonate reservoir[J]. Earth Science Frontiers, 2011, 18(4): 181-192.

[25] 张抗.塔河油田的发现及其地质意义[J].石油与天然气地质,1999,20(2):120-124.
ZHANG Kang. The discovery of Tahe oilfield and its geologic significance[J]. Oil & Gas Geology, 1999, 20(2): 120-124.

[26] 周新源,王招明,杨海军,等.中国海相油气田勘探实例之五:塔中奥陶系大型凝析气田的勘探和发现[J].海相油气地质,2006,11(1):45-51.
ZHOU Xinyuan, WANG Zhaoming, YANG Haijun, et al. Cases of discovery and exploration of marine fields in China (Part 5): Tazhong Ordovician condensate field in Tarim Basin[J]. Marine Origin Petroleum Geology, 2006, 11(1): 45-51.

[27] 马永生,郭旭升,郭彤楼,等.四川盆地普光大型气田的发现与勘探启示[J].地质论评,2005,51(4):477-480.
MA Yongsheng, GUO Xusheng, GUO Tonglou, et al. Discovery of the large-scale Puguang gas field in the Sichuan Basin and its enlightenment for hydrocarbon prospecting [J]. Geological Review, 2005, 51(4): 477-480.

[28] 赵贤正,金凤鸣,王权,等.中国东部超深超高温碳酸盐岩潜山油气藏的发现及关键技术:以渤海湾盆地冀中坳陷牛东1潜山油气藏为例[J].海相油气地质,2011,16(4):1-10.
ZHAO Xianzheng, JIN Fengming, WANG Quan, et al. A super-deep and superhigh temperature carbonate buried-hill reservoir in eastern China: discovery and the key exploration technology of Nudong-1 buried-hill oil and gas reservoir in Jizhong Depression, Bohaiwan Basin[J]. Marine Origin Petroleum Geology, 2011, 16(4): 1-10.

[29] SCHMOKER J W, HALLEY R B. Carbonate porosity versus depth: a predictable relation for South Florida[J]. AAPG Bulletin, 1982, 66(12): 2561-2570.

[30] ZHU Dongya, JIN Zhujun, HU Wenxuan. Hydrothermal recrystallization of the Lower Ordovician dolomite and its significance to reservoir in northern Tarim Basin[J]. Science China Earth Sciences, 2010, 53(3): 368-381.

[31] JIN Zhijun, ZHU Dongya, HU Wenxuan, et al. Mesogenetic dissolution of the Middle Ordovician limestone in the Tahe oilfield of Tarim Basin, NW China[J]. Marine and Petroleum Geology, 2009, 26(6): 753-763.

[32] MENG Qingqiang, ZHU Dongya, HU Wenxuan, et al. Dissolution-filling mechanism of atmospheric precipitation controlled by both thermodynamics and kinetics[J]. Science China Earth Sciences, 2013, 56(12): 2150-2159.

[33] 朱东亚,孟庆强,金之钧,等.富 CO_2 深部流体对碳酸盐岩的溶蚀—充填作用的热力学分析[J].地质科学,2012,47(1):187-201.
ZHU Dongya, MENG Qingqiang, JIN Zhijun, et al. Thermodynamic analysis for carbonate dissolution-filling under influence of CO_2-rich deep fluid[J]. Chinese Journal of Geology, 2012, 47(1): 187-201.

[34] 朱东亚,孟庆强,胡文瑄,等.塔里木盆地塔北和塔中地区流体作用环境差异性分析[J].地球化学,2013,42(1):82-94.
ZHU Dongya, MENG Qingqiang, HU Wenxuan, et al. Differences between fluid activities in the central and north Tarim Basin[J]. Geochimica, 2013, 42(1): 82-94.

[35] 朱东亚,金之钧,孙冬胜,等.南方震旦系灯影组热液白云岩化及其对储层形成的影响研究:以黔中隆起为例[J].地质科学,2014,49(1):161-175.
ZHU Dongya, JIN Zhijun, SUN Dongsheng, et al. Hydrothermally dolomitized reservoir bed in Sinian Dengying Formation, northern China: an example from Central Guizhou Uplift[J]. Chinese Journal of Geology, 2014, 49(1): 161-175.

[36] 孟庆强,朱东亚,解启来,等.塔中和巴楚地区深部流体活动控制因素及有利区预测[J].石油实验地质,2011,33(6):597-601.

MENG Qingqiang,ZHU Dongya,JIE Qilai,et al.Controlling factors for deep fluid activity and prediction of positive effect area in middle Tarim and Bachu regions[J].Petroleum Geology & Experiment,2011,33(6):597-601.

[37] 马永生,蔡勋育,赵培荣.元坝气田长兴组—飞仙关组礁滩相储层特征和形成机理[J].石油学报,2014,35(6):1001-1011.
MA Yongsheng,CAI Xunyu,ZHAO Peirong.Characteristics and formation mechanisms of reef-shoal carbonate reservoirs of Changxing-Feixianguan formations,Yuanba gas field[J].Acta Petrolei Sinica,2014,35(6):1001-1011.

[38] 蒋小琼,管宏林,郑和荣,等.四川盆地普光气田飞仙关组白云岩储层成因探讨[J].石油实验地质,2014,36(3):332-336.
JIANG Xiaoqiong,GUAN Honglin,ZHENG Herong,et al.Discussion on origin of dolomite reservoirs in Feixianguan Formation,Puguang Gas Field,Sichuan Basin[J].Petroleum Geology & Experiment,2014,36(3):332-336.

[39] 黄善炳.金湖凹陷阜宁组砂岩中片钠铝石特征及对物性的影响[J].石油勘探与开发,1996,23(2):32-34.
HUANG Shanbing.The character of dawsonite in sandstone reservoirs of the Funing Formation in Jinhu Sag and its influence on reservoir properties[J].Petroleum Exploration and Development,1996,23(2):32-34.

[40] 高玉巧,刘立,杨会东,等.松辽盆地孤店二氧化碳气田片钠铝石的特征及成因[J].石油学报,2007,28(4):62-67.
GAO Yuqiao,LIU Li,YANG Huidong,et al.Characteristics and origin of dawsonite in Gudian carbon dioxide gas field of Songliao Basin[J].Acta Petrolei Sinica,2007,28(4):62-67.

[41] 董林森,刘立,曲希玉,等.松辽盆地南部红岗油田青山口组片钠铝石的结晶特征及成因探讨[J].吉林大学学报(地球科学版),2009,39(6):1031-1041.
DONG Linsen,LIU Li,QU Xiyu,et al.Crystal characteristics and genesis of dawsonite of the Qingshankou Formation in the Honggang oilfield in the southern Songliao Basin[J].Journal of Jilin University(Earth Science Edition),2009,39(6):1031-1041.

[42] 孟庆强,张刘平,邹安德.富 CO_2 流体对深部碎屑储层影响机制模拟研究[J].石油天然气学报,2007,29(2):45-49.
MENG Qingqiang,ZHANG Liuping,ZOU Ande.Simulation study on the mechanism of effect of CO_2 enriched fluid on deep clastic reservoirs[J].Journal of Oil and Gas Technology,2007,29(2):45-49.

[43] 卢焕章,范宏瑞,倪培,等.流体包裹体[M].北京:科学出版社,2004:48.
LU Huanzhang,FAN Hongrui,NI Pei,et al.Fluid inclusions[M].Beijing:Science Press,2004:48.

[44] HYATT J A.Liquid and supercritical carbon dioxide as organic solvents[J].The Journal of Organic Chemistry,1984,49(26):5097-5101.

[45] STAHL E,SCHUETZ E,MANGOLD H K.Extraction of seed oils with liquid and supercritical carbon dioxide[J].Journal of Agricultural and Food Chemistry,1980,28(6):1153-1157.

[46] BEVERIDGE T,HARRISON J E.Microscopic structural components of sea buckthorn(Hippophae rhamnoides L.)juice prepared by centrifugation[J].LWT-Food Science and Technology,2001,34(7):458-461.

[47] KAZARIAN S G.Enhancing high-throughput technology and microfluidics with FTIR spectroscopic imaging[J].Analytical and Bioanalytical Chemistry,2007,388(3):529-532.

[48] SUBRAMANIAM V,KIRSCH A K,RIVERA-POMAR R V,et al.Scanning near-field optical microscopy and microspectroscopy of green fluorescent protein in intact Escherichia coli bacteria[J].Journal of Fluorescence,1997,7(4):381-385.

[49] BONDAR E,KOEL M.Application of supercritical fluid extraction to organic geochemical studies of oil shales[J].Fuel,1998,77(3):211-213.

[50] OKAMOTO I,LI Xiaochun,OHSUMI T.Effect of supercritical CO_2 as the organic solvent on cap rock sealing performance for underground storage[J].Energy,2005,30(11/12):2344-2351.

[51] DIEP P,JORDAN K D,JOHNSON J K,et al.CO_2-fluorocarbon and CO_2-hydrocarbon interactions from first-principles calculations[J].The Journal of Physical Chemistry A,1998,102(12):2231-2236.

[52] 谷丽冰,李治平,欧瑾.利用二氧化碳提高原油采收率研究进展[J].中国矿业,2007,16(10):66-69.
GU Libing,LI Zhiping,OU Jin.The existing state of enhanced oil recovery by utilizing carbon dioxide[J].China Mining Magazine,2007,16(10):66-69.

[53] HOFFMANN C F,HENLEY R W,HIGGINS N C,et al.Biogenic hydrocarbons in fluid inclusions from the aberfoyle tin-tungsten deposit,Tasmania,Australia[J].Chemical Geology,1988,70(4):287-299.

[54] DUTKIEWICZ A,RIDLEY J,BUICK R.Oil-bearing CO_2-CH_4-H_2O fluid inclusions:oil survival since the Palaeoproterozoic after high temperature entrapment[J].Chemical Geology,2003,194(1/3):51-79.

[55] 孙樯,谢鸿森,郭捷,等.地球深部流体与油气生成及运移浅析[J].地球科学进展,2000,15(3):283-288.
SUN Qiang,XIE Hongsen,GUO Jie,et al.Fluids in deep earth and origin and migration of oil and gas[J].Advances in Earth Science,2000,15(3):283-288.

[56] 马安来,孙红军,郑磊,等.桑托斯盆地 Jupiter 油气田富含 CO_2 油气藏形成机制[J].石油与天然气地质,2017,38(2):371-378.
MA Anlai,SUN Hongjun,ZHENG Lei,et al.A study on forming mechanisms of CO_2-rich reservoirs in Jupiter oilfield,Santos Basin,Brazil[J].Oil & Gas Geology,2017,38(2):371-378.

[57] 何家雄,祝有海,翁荣南,等.南海北部边缘盆地泥底辟及泥火山特征及其与油气运聚关系[J].地球科学(中国地质大学学报),2010,35(1):75-86.
HE Jiaxiong,ZHU Youhai,WENG R N,et al.Characters of north-west mud diapirs volcanoes in South China Sea and relationship between them and accumulation and migration of oil and gas[J].Earth Science(Journal of China University of Geosciences),2010,35(1):75-86.

[58] LIU Quanyou,ZHU Dongya,JIN Zhijun,et al.Carbon capture and storage for long-term and safe sealing with constrained natural CO_2 analogs[J].Renewable and Sustainable Energy Reviews,2023,171:113000.

(编辑　韩　彧)