

超深层大型古老碳酸盐岩油藏超长时限保存机制

——以塔里木盆地北部地区为例

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摘要:传统“黄金带”理论将液态烃的稳定保存局限于浅-中埋深及有限温度区间。然而,近年来超深层古老碳酸盐岩油藏的重大发现打破了这一经典认知,其“超长时限”保存机制已成为制约深层油气勘探评价的关键科学问题。以塔里木盆地北部地区为例,系统解析了该区古老油藏的石油地质特征、成藏期次与改造机制,揭示了其超长时限保存的内在规律,主要取得以下认识:①静态要素的优越配置是保存的物质基础。下寒武统玉尔吐斯组优质烃源岩提供持续油源;多期岩溶与断裂耦合作用塑造了规模宏大的缝洞型储集体;上奥陶统巨厚泥岩构成了高突破压力的多级区域封盖体系。三者时在-空上良好匹配,奠定了大型油藏形成的先天条件。②“冷盆”背景与“晚期快速深埋”的耦合是保存的动态关键。该盆地长期处于低地温梯度背景,且呈现早期持续浅埋、晚期快速深埋的埋藏史特征,尽管主成藏期(约250 Ma)后油藏最终埋深大于7 000 m,但处于高温($>160^{\circ}\text{C}$)环境的时间极短($<5\text{ Ma}$),导致时-温补偿效应显著不足,从根本上抑制了原油热裂解;同时,高压或超压环境的耦合作用进一步降低了原油裂解风险。③成藏后弱次生改造是维持液态烃相态和地球化学稳定性的关键保障。油藏后期经历的热硫酸盐还原(TSR)、生物降解和气洗等作用微弱,原油地球化学性质保持稳定,呈现出典型的“早期成藏、晚期深埋保存”特征。综上所述,该研究构建了超深层古老油藏超长时限的保存模式,揭示了时-温-压耦合抑制原油裂解的核心机制。该成果突破了传统“黄金带”理论的限制,为古老克拉通盆地超深层液态烃的勘探潜力评价与有利区带优选提供了新的理论指导。

关键词:时-温补偿效应;超长时限;油藏保存机制;古老碳酸盐岩油藏;超深层;塔里木盆地

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Preservation mechanisms of ultra-deep, giant, ancient carbonate oil reservoirs over ultralong timescales: A case study of the northern Tarim Basin

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Abstract: The conventional “Golden Zone” theory restricts the stable preservation of liquid hydrocarbons to shallow-to-moderate burial depths and a limited temperature range. However, major discoveries of ultra-deep ancient carbonate oil reservoirs in recent years have challenged this classical understanding. The preservation mechanisms over ultralong timescales have become a critical scientific issue constraining the evaluation of deep petroleum exploration potential. The intrinsic controls on the ultralong-term preservation of ancient oil reservoirs in the northern Tarim Basin were revealed by systematically analyzing their petroleum geological characteristics, hydrocarbon accumulation stages, and post-accumulation alteration mechanisms. As indicated by the research results, (1) the favorable configuration of static geological elements provides the material foundation for preservation. High-quality source rocks of the Lower Cambrian Yuertusi Formation supplied a sustained oil charge; multi-stage karstification coupled with faulting created large-scale fracture-cavity reservoirs; and extremely thick Upper Ordovician mudstones formed a multi-level regional sealing system with high breakthrough pressure. The perfect spatiotemporal matching of these three elements laid the inherent

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foundation for the formation of giant oil reservoirs. (2) The coupling of a “cold basin” thermal regime with “late-stage rapid deep burial” is the dynamic key to preservation. The basin in this area has maintained a low geothermal gradient over a long geological period and is characterized by a burial history of sustained shallow burial in the early stage followed by rapid deep burial in the late stage. Although the reservoirs were ultimately buried to a depth of more than 7 000 m after the main accumulation period at approximately 250 Ma, they were exposed to high-temperature conditions ($>160\text{ }^{\circ}\text{C}$) for an extremely short duration ($<5\text{ Ma}$), resulting in a markedly insufficient time-temperature compensation effect and fundamentally suppressing the thermal cracking of crude oil. In addition, the coupled effect of high-pressure and overpressure conditions further reduced the risk of crude oil cracking. (3) Weak post-accumulation secondary alteration is the key guarantee for maintaining the liquid hydrocarbon phase state and geochemical stability of the reservoirs. The reservoirs experienced only weak late-stage alteration, including thermochemical sulfate reduction (TSR), biodegradation, and gas washing. As a result, the geochemical properties of the crude oil remained stable, showing the typical characteristics of “early accumulation and late-stage deep-burial preservation.” In summary, this study establishes a preservation model for ultra-deep ancient oil reservoirs over ultralong timescales and reveals the core mechanism of time-temperature-pressure coupled inhibition. These findings break through the limitations of the traditional “Golden Zone” theory and provide new theoretical guidance for evaluating the exploration potential of ultra-deep liquid hydrocarbons in ancient cratonic basins and selecting favorable zones.

Key words: time-temperature compensation effect, reservoir preservation mechanism, ancient carbonate oil reservoir, ultra-deep reservoir, Tarim Basin

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传统的“黄金带”理论认为,全球约90%的油气资源赋存于地层温度 $60\sim 120\text{ }^{\circ}\text{C}$ 的浅-中埋深区间,该温-压窗口常被视为油气生成、运移与保存的最优环境^[1-2]。然而,随着全球油气勘探不断向超深层(埋深 $>6\ 000\text{ m}$)拓展,迄今已发现超深层油气藏约305个^[3]。其中,相当一部分储层的温度及埋深显著超出“黄金带”上限,对传统理论的普适性提出了严峻挑战(图1a,b)。更为引人注目的是,形成于古生代及以前、历经多期构造运动与漫长地质演化的古老碳酸盐岩油藏,理论上原生气极难保存,但近年来国内外仍不断取得重大勘探突破^[4-6]。这些具有“超长地质时限”的古老油藏,究竟是如何在深埋高温环境下得以完好保存的?解答这一核心科学问题,不仅有助于完善深层油气保存理论,更对超深层油气勘探部署与潜力评价具有重要的指导意义^[7-10]。

塔里木盆地是中国典型的超深层含油气盆地,超深层碳酸盐岩油气资源占比高达70%^[11]。在盆地北部奥陶系,已发现哈拉哈塘、顺北、富源及富满等一系列大型超深层油气田。这些形成于古生代的古老油藏稳定保存至今,其主体储层现今温度($150\sim 190\text{ }^{\circ}\text{C}$)与埋深已显著突破传统“黄金带”液态烃窗口

上限(约 $150\text{ }^{\circ}\text{C}$)(图1c),却依然以液态烃为主,构成了挑战传统温度界限的典型案例。因此,塔北地区是研究超深层碳酸盐岩古老油藏保存机制的理想实例^[11-12]。针对该类油藏的保存机制,前人已从多角度开展了深入探讨,积累了丰富认识。部分学者聚焦于静态地质要素,强调优质生-储-盖组合与稳定圈闭的基础性作用^[13-14];另一些研究则关注动态演化过程,揭示了长期低地温梯度与晚期快速深埋的关键影响^[15-16];还有学者通过地球化学与构造背景分析,分别指出了流体弱蚀变作用和稳定构造环境的重要性^[17-18]。此外,有研究表明高压或超压(流体压力大于静水压力)可以延缓烃源岩的热演化并抑制原油裂解,有利于超深层液态烃的持续生成与保存^[19-23];但也有学者指出高压或超压对于原油裂解的抑制作用有限^[24]。总体而言,现有研究从各自角度深化了对单一控制因素的认识,但超深层古老油藏的保存本质上是多因素在漫长地质历史中时-空耦合的复杂过程。目前,尚缺乏将这些分散的静态要素与动态过程进行有效整合、系统揭示其内在联系与主控要素的统一理论框架。基于上述分析,本文以塔里木盆地北部地区为研究靶区,旨在系统梳理该区古老油藏的石油

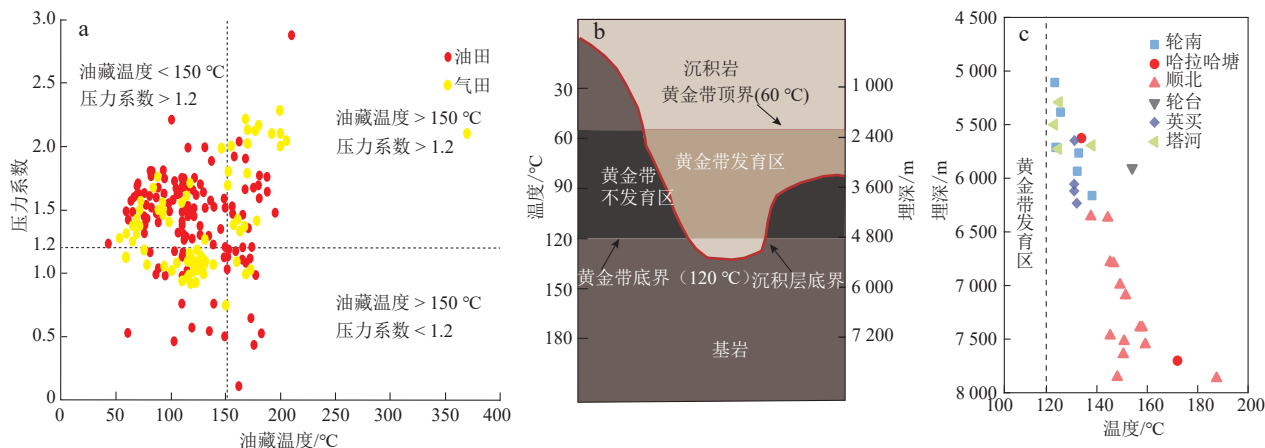


图1 超深层油藏温度分布与传统黄金带温度分布对比

Fig. 1 Comparison of temperature distribution between ultra-deep oil reservoirs and the traditional Golden Zone

a. 全球埋深> 5 000 m的深层油气田温度与压力系数分布^[25]; b. 黄金带温度和埋深分布范围示意图^[26]; c. 塔北地区超深层油气藏温度-埋深分布 (数据来自文献[18, 27-30])

地质特征,明确其“生-储-盖”静态要素的优越配置;精准厘定油气成藏期次,为主成藏期后的演化历程提供时间标尺;深入剖析成藏后经历的各类改造作用及其控制因素,揭示“弱改造”的内在机理。在此基础上,综合构建超深层古老碳酸盐岩油藏的超长时限保存模式,阐明其主控机制。研究成果有望突破传统“黄金带”理论的认识局限,为古老克拉通盆地超深层液态烃的勘探潜力评价与有利区带优选提供新的理论指导。

1 古老油气藏的石油地质特征

超深层古老碳酸盐岩油藏能够实现“超长时限”保存,首要前提是具备优越的“生-储-盖”静态要素组合。这些要素不仅是油气成藏的物质基础,其特殊的性质与演化历史更为油藏的长期保存提供了先决条件。本章以塔里木盆地北部地区为例,系统阐述下寒武统烃源岩、奥陶系储层及上奥陶统盖层的核心特征,揭示其时空匹配关系及构成油藏超长期保存的地质基础。

1.1 烃源岩特征:持续供烃的物质保障

塔里木盆地主要发育下寒武统、石炭系-二叠系和三叠系-侏罗系3套烃源岩。其中,分布于塔北及北部坳陷区的下寒武统玉尔吐斯组黑色页岩,是塔北地区早古生代海相主力烃源岩,厚度为6~25 m^[14,31]。以轮探1井为例,其钻揭的玉尔吐斯组下段黑色页岩有机质丰度极高,总有机碳含量(TOC)最高可达29.78% (图2a),是中国目前已发现TOC最高的海相烃源

岩^[32]。地球化学指标显示,玉尔吐斯组烃源岩的生烃母质主要来源于低等底栖与浮游生物,沉积于还原环境(图2d);干酪根元素组成和生物标志化合物特征共同指示其有机质类型以II₂型为主(图2b,c);镜质体反射率(R_o)介于1.5%~1.7%,处于高成熟凝析油-湿气阶段^[33-34]。

对于超长时限油藏的保存而言,相较于烃源岩的高有机质丰度,其持续的生烃能力与供烃能力更为关键。盆地模拟结果显示,玉尔吐斯组烃源岩经历了多期热演化,主生烃期集中在加里东晚期和海西晚期^[35]。加里东晚期,满加尔坳陷区的烃源岩率先进入生烃高峰,生成的油气在继承性走滑断裂系统的输导下,开始向塔北隆起大规模运移。但受海西运动早期构造-热事件影响,该期充注的油气遭受严重破坏,多以固体沥青形式残留^[36]。至海西运动中、晚期,随着塔北地区持续沉降,玉尔吐斯组烃源岩再次进入大规模生烃阶段,油气的再次生成与充注为超深层古老油藏的形成奠定了坚实的物质基础^[37]。喜马拉雅运动以来,塔北地区的油气充注转为以天然气为主^[14,38],液态烃补注整体较弱。因此,海西晚期是塔北地区奥陶系油藏最主要的生烃与成藏期,更为重要的是,自海西晚期成藏以来,塔里木盆地长期维持低地温梯度背景,显著延缓了玉尔吐斯组烃源岩的热演化进程,使其至今仍保有良好的生烃潜力^[39]。

1.2 储层特征:高能沉积与多期改造耦合

超深层碳酸盐岩储层埋深大,温-压高,原生孔隙多被强烈破坏,基质孔隙度与渗透率普遍较低^[37]。因

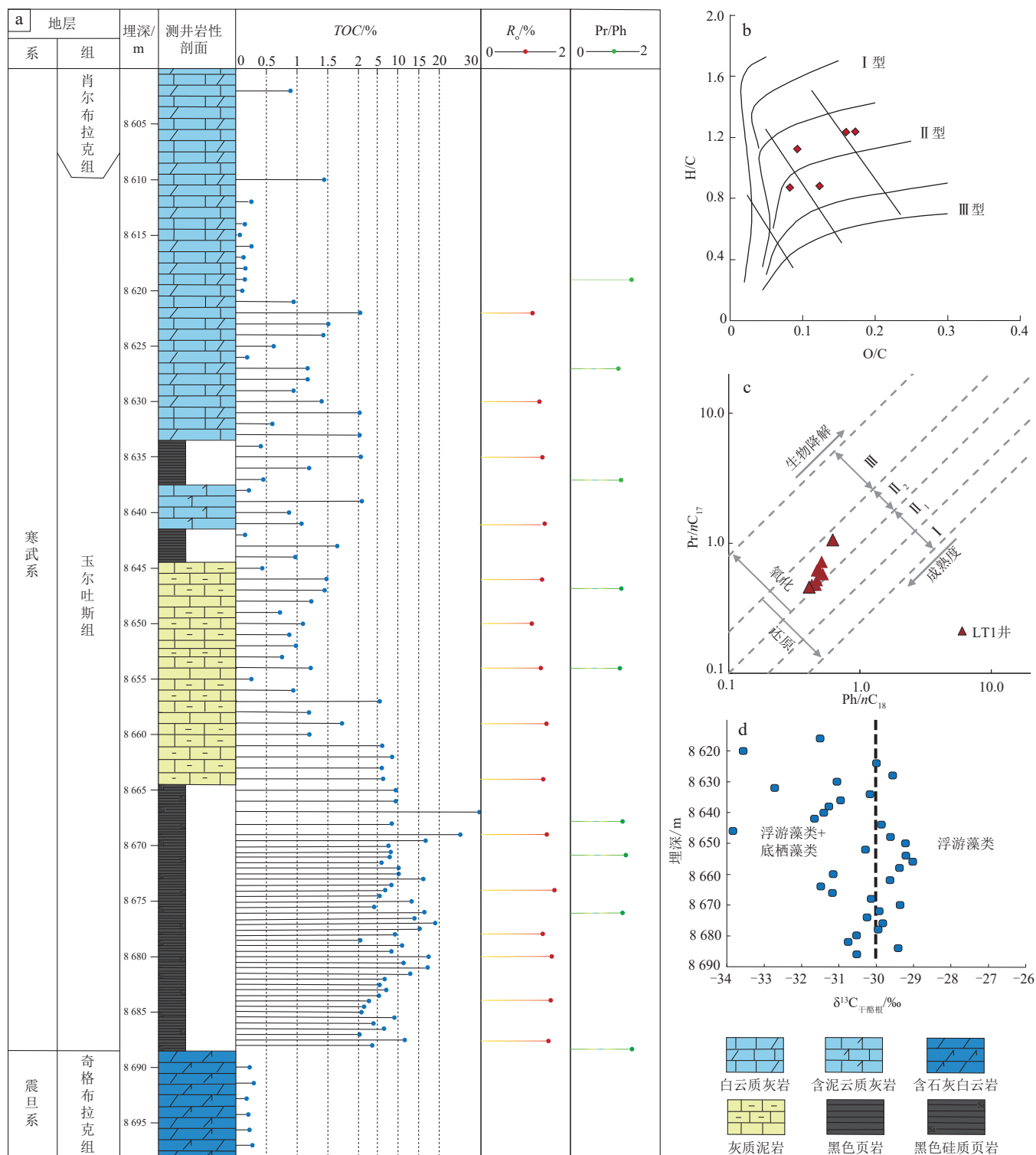


图2 塔北地区轮探1井玉尔吐斯组烃源岩地球化学特征

Fig. 2 Comprehensive geochemical characteristics of source rocks from the Yuertusi Formation in well Luntan 1, northern Tarim Basin

a. 地球化学特征综合柱状图(据文献[30]修改, R_o 数据来自文献[33], Pr/Ph数据来自文献[34]); b. H/C-O/C 干酪根类型判别图版^[33]; c. Pr/nC₁₇-Ph/nC₁₈ 交会图(数据来自文献[33]); d. 干酪根碳同位素判别母质来源图版^[34]

TOC: 总有机碳含量; R_o : 镜质体反射率; Pr/Ph: 姥鲛烷/植烷含量比值; H/C: 氢/碳原子数比值; O/C: 氧/碳原子数比值; Pr/nC₁₇: 姥鲛烷/正十七烷含量比值; Ph/nC₁₈: 植烷/正十八烷含量比值; δ¹³C_{干酪根}: 干酪根稳定碳同位素比值

此, 优质储层的形成高度依赖于次生改造作用。溶蚀孔洞与构造裂缝耦合形成的大型复杂缝洞系统, 构成

了古老油藏的主要储集空间^[40-41], 其储集类型以溶蚀孔洞型、裂缝型及裂缝-孔洞型为主(图3a,c)^[42-43]。

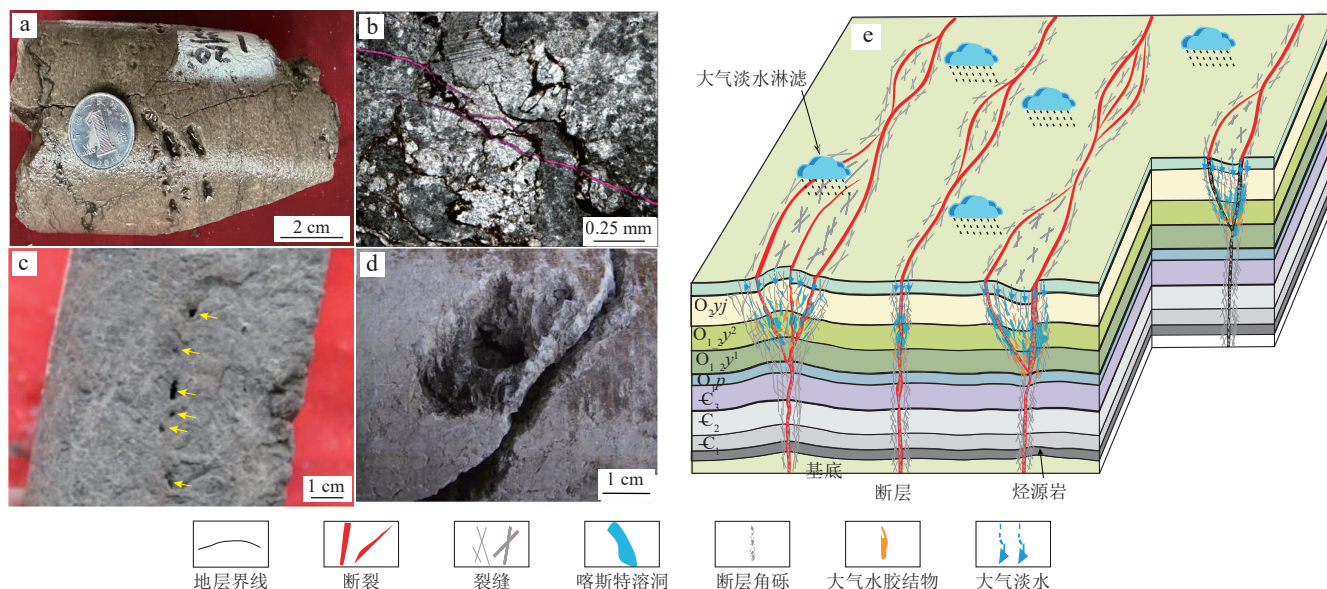


图3 塔北地区古老油藏储层孔隙结构照片(a—d)及成储模式示意图(e)

Fig. 3 Pore structure (a—d) and reservoir formation model (e) of ancient oil reservoirs in the northern Tarim Basin

a. 顺北隆2井,埋深8 276.55 m,鹰山组,溶蚀孔及裂缝,岩心照片^[49];b. YueM2井,埋深7 217.60 m,一间房组,构造裂缝及压裂缝,铸体薄片镜下照片^[50];c. J2-3井,埋深7 080.50 m,一间房组,串珠状溶蚀孔,岩心照片^[51];d. HD27井,一间房组,埋深6 285.50 m,微裂缝及未充填洞穴,岩心照片^[52];e. 顺托果勒低凸起一间房组断溶体储层成因模式图^[51]

(ϵ_1 为下寒武统; ϵ_2 为中寒武统; ϵ_3 为上寒武统; O_p 为下奥陶统蓬莱坝组; $O_{1-2}y^1$ 为中-下奥陶统鹰山组下段; $O_{1-2}y^2$ 为中-下奥陶统鹰山组上段; $O_{2y}j$ 为中奥陶统一间房组。)

塔北地区的主力储集层系为奥陶系一间房组与鹰山组的岩溶缝洞型灰岩,是顺北和哈拉哈塘等大型油气田的核心产层^[14]。其优质储层的发育关键可概括为:沉积相带奠定物质基础,多期断裂与流体溶蚀主导核心改造^[44-46]。具体表现为:①沉积相带奠定物质基础:高能滩相沉积为后期溶蚀提供了易溶的矿物组合和初始孔隙空间。②多期断裂构建储集格架:加里东—海西期的多阶段构造应力重组与断裂的继承性活动,导致塔北地区发育了多期次、多组系的大型走滑断裂系统^[47],这些断裂及其伴生的裂缝网络不仅极大改善了储层的渗透性,更为流体的长距离运移提供了高效通道。③多期流体溶蚀扩大储集空间:加里东早期的构造隆升使储层出露地表,经历了强烈的风化剥蚀与大气淡水淋滤,形成了大量的溶蚀孔洞和微裂缝(图3b,d);在后期埋藏过程中,有机酸等酸性流体沿断裂系统持续运移,进一步深化了溶蚀作用^[48]。最终,层间岩溶作用与走滑断裂带的多期活动相互叠加,共同塑造了现今规模宏大的碳酸盐岩缝洞型岩溶储集体(图3e)。

1.3 盖层特征:多级封盖与深部塑性变形

稳定分布的区域性厚层盖层是大型古老油藏得以长期保存的必要条件,直接控制着油气的富集程度与

纵向分布格局^[53]。常规盖层岩性主要包括泥页岩、蒸发岩和致密碳酸盐岩^[54-55]。塔里木盆地超深层主要发育4套区域性盖层:下寒武统玉尔吐斯组泥页岩,中寒武统阿瓦塔格组与沙依里克组膏盐岩,中-下奥陶统致密碳酸盐岩,以及上奥陶统吐木休克组泥灰岩和桑塔木组泥岩^[14]。

对于塔北地区奥陶系油藏的保存而言,上奥陶统盖层发挥着无可替代的核心作用。其中,吐木休克组(厚30~50 m)由连续稳定的泥岩与致密灰岩构成,作为一间房组储层的直接盖层^[56];桑塔木组(厚200~700 m)以暗色泥岩夹灰岩为主,构成了该区奥陶系古老油藏的优质区域盖层。这些盖层岩性致密,毛细管突破压力极高,构成了垂向封堵的核心屏障^[57]。它们与深部寒武系膏盐岩和致密碳酸盐岩等共同构建了纵向上的多级封盖体系,极大提升了封堵的稳定性与长期有效性。更为关键的是,这套盖层在深部条件具备优越的塑性变形能力。岩石力学实验与分析表明,泥页岩盖层的力学性质受深部围压影响显著^[58],随着埋深和围压的增加,泥页岩盖层的屈服极限、极限强度和塑性变形能力整体增强(图4),不易发生脆性破裂,从而显著提升了其封闭有效性^[10,59]。这一塑性特征使得盖层能够有效抵御断裂的穿透性破坏,进而维护封盖层的整体性和长期有效性。

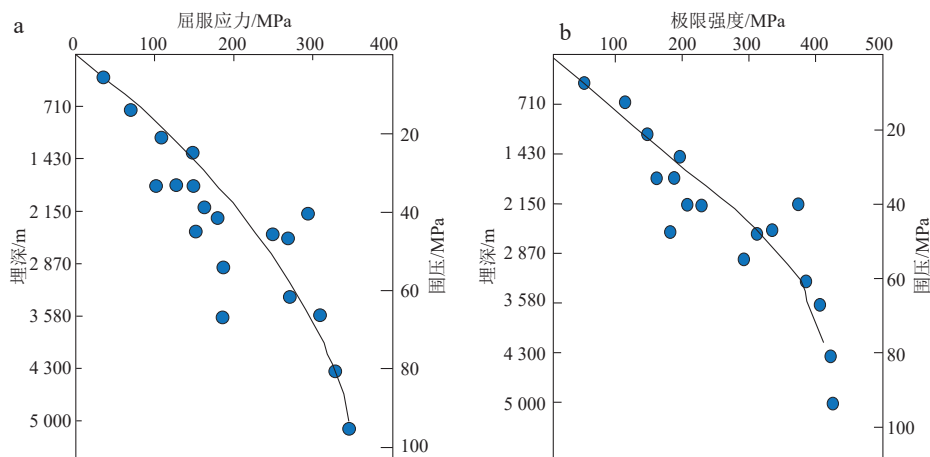


图4 江汉盆地泥岩盖层围压和埋深与屈服应力及极限强度关系^[59]

Fig. 4 Variation of yield stress and ultimate strength for mudstone caprock with confining pressure and burial depth, Jiangnan Basin^[59]

a. 围压(埋深)与屈服应力的关系; b. 围压(埋深)与极限强度的关系

综上所述,塔北地区超深层古老碳酸盐岩油藏具备优越且匹配的生-储-盖要素组合(图5)。持续供烃的烃源灶、高效改造的缝洞型储集体以及稳定的多级封盖体系,在时-空上实现了有效配置,共同奠定了塔北地区超深层古老油藏形成与长期保存的物质基础。

2 古老油藏成藏时间的确定

准确厘定超深层古老油藏的主要成藏期次,是解析其“超长时限”保存机制的首要时间前提。它不仅界定了油气大规模聚集与保存过程的起点,更为评估油藏所经历的构造-热事件序列、埋藏-抬升历史以及次生蚀变作用的持续时间提供了关键的年代学框架^[60-61]。本节旨在通过多方法综合定年,精确界定塔北地区奥陶系古老油藏的主成藏期,并阐述该时间节点对理解后续演化与保存机制的科学意义。

2.1 古老油藏成藏时间综合判识技术

针对古老碳酸盐岩油藏的定年,研究方法已从早期的定性地质分析发展为现今高精度的定量-半定量技术体系。然而,塔里木盆地碳酸盐岩储层具有成岩演化复杂、多期流体活动叠加、后期改造强烈等特点,单一定年方法往往难以获得可靠结果。因此,必须遵循“岩相学约束-显微测温-同位素定年-盆地模拟”的综合思路,实现多方法的相互验证与约束。首先,通过高精度岩相学观察,精确厘定与油气包裹体共生的盐水包裹体的成岩期次,区分原生与次生包裹体,以确保测温数据的可靠性^[62]。其次,将获得的均一温度数据

投影到基于独立参数[如磷灰石裂变径迹、(U-Th)/He低温热年代学数据]约束建立的精细埋藏史-热演化史模型中,从而将温度转化为地质时间。近年来,储层中与油气活动同期的自生伊利石(K-Ar)/(⁴⁰Ar-³⁹Ar)定年、方解石脉U-Pb定年以及沥青Re-Os定年等同位素绝对定年技术的突破^[63-64],为传统方法提供了独立的年代学约束,显著提高了定年的精度和可信度。最后,将上述温度-时间信息与盆地演化历史整合,通过盆地模拟软件重建油藏的埋藏史、热史和生烃史,以检验定年结果的合理性与一致性。这种多方法交叉验证的思路,是厘清塔里木盆地这类复杂叠合盆地成藏序列的必要前提,也是本文确定主成藏期的方法论基础。

2.2 塔北地区古老油藏主成藏期

基于上述多方法综合研究,塔北地区超深层奥陶系古老油藏的成藏时间已得到清晰界定。对哈拉哈塘、顺北、托甫台、英买力及富源等油田的大量研究表明,尽管部分地区存在加里东期(如顺北地区)的早期油气充注痕迹以及喜马拉雅期的晚期天然气充注,但其主成藏期(即形成现今保存储量的关键油气充注事件)均一致指向海西晚期(约250 Ma)(图6)^[7,41,60,63]。

这一结论得到多方面证据的支持:首先,基于岩相学约束的流体包裹体证据为成藏时间提供了半定量约束。奥陶系储层中与油气充注相关的烃类包裹体,其伴生的盐水包裹体均一温度主峰在单井埋藏史的投影时间主要为海西晚期^[65]。其次,同位素绝对定年技术为上述时间框架提供了独立的年代学约束:哈拉哈塘油田储层固体沥青的Re-Os等时线年龄为285 Ma ±

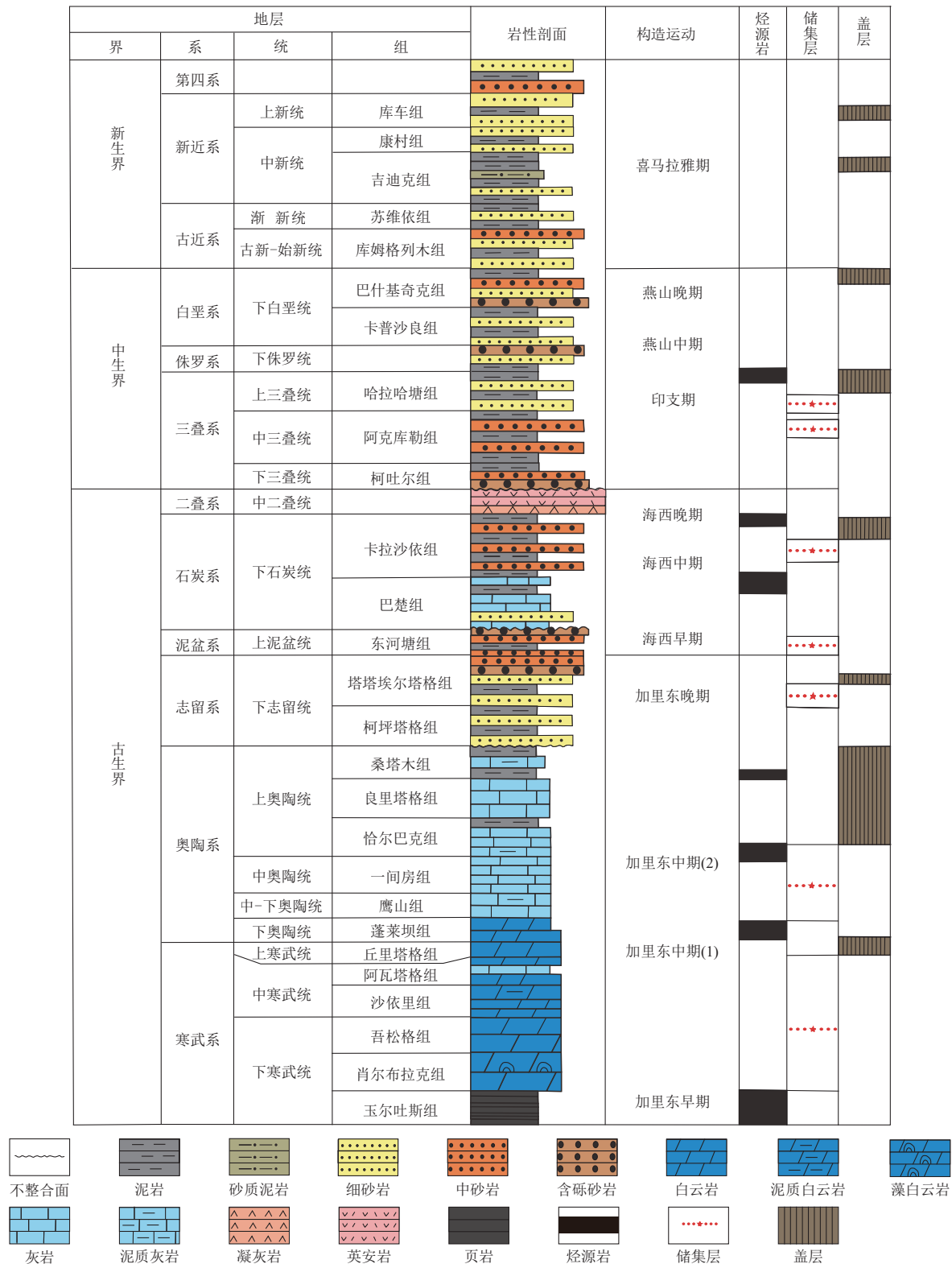


图5 塔北地区地层综合柱状图(据文献[60]修改)

Fig. 5 Composite stratigraphic column of the northern Tarim Basin (modified after reference [60])

48 Ma^[63], 英买2油田K-Ar年龄为270 Ma ± 20 Ma^[7], 均集中在海西晚期^[38, 63]。最后, 通过盆地模拟检验了成藏时间与石油地质条件的时-空匹配性。在流体包裹体与同位素绝对年龄的共同约束下(图6d), 盆地模

拟重建的塔北地区埋藏史表明, 海西晚期塔北地区下寒武统玉尔吐斯组烃源岩再次进入生油高峰^[37]; 同时, 加里东期—海西期形成的岩溶缝洞储集体和大型走滑断裂系统已发育完善, 为油气的大规模运聚提供

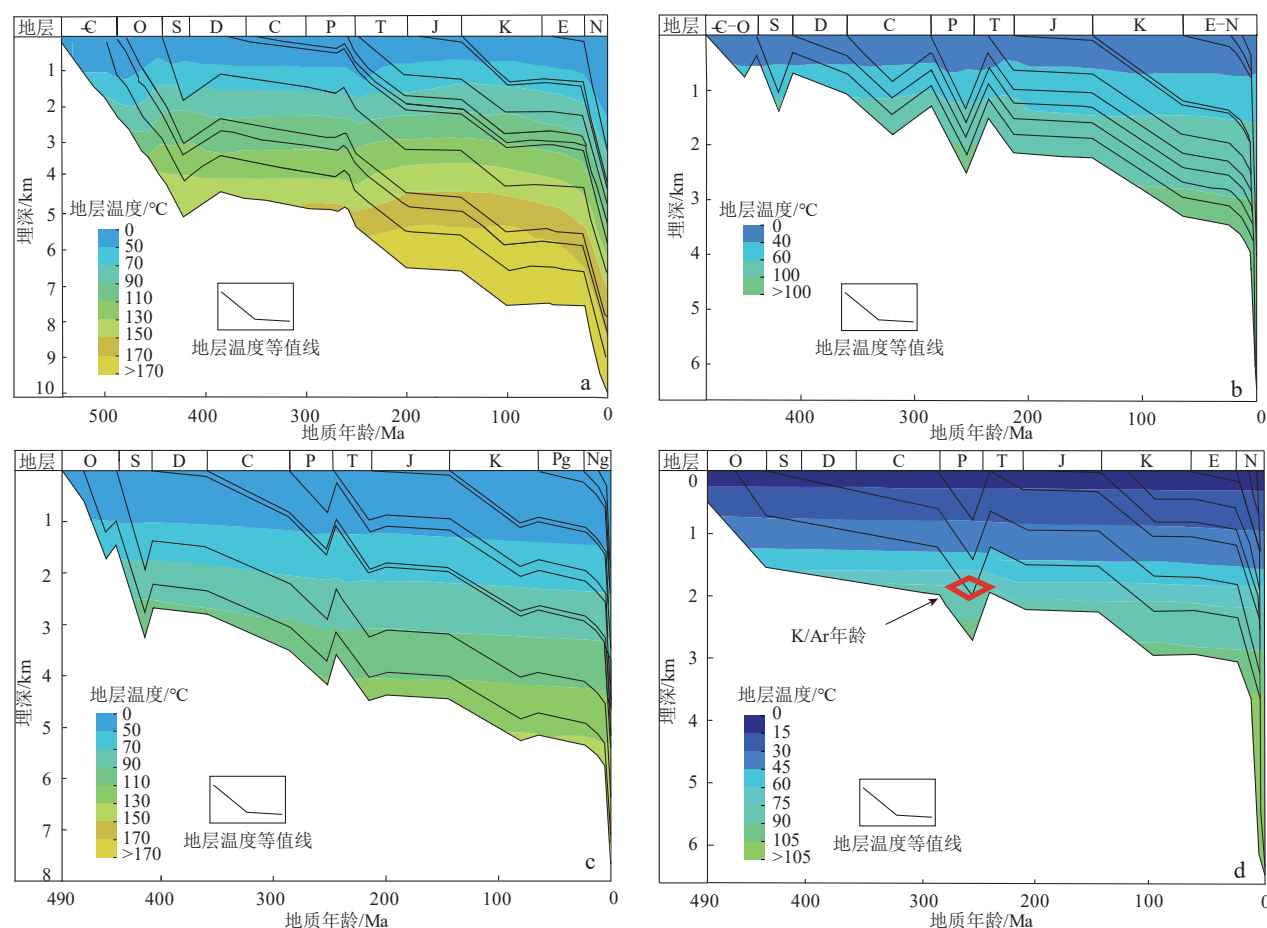


图6 塔北地区古老油藏埋藏史

Fig. 6 Burial history of ancient oil reservoirs in the northern Tarim Basin

a. 顺北5井(据文献[65]修改); b. 哈拉哈塘油田(据文献[63]修改); c. 富源1井(据文献[29]修改); d. 英艾2油田(据文献[7]修改)

了优越的时-空匹配条件。此后,油藏整体进入持续埋藏阶段。

2.3 早期成藏对古老碳酸盐岩油气保存至今的意义

早期油气充注对储层物理性质及后期成藏演化具有深远影响。首先,油气与储层岩石的长期接触可诱导岩石润湿性由亲水向亲油转变。这一润湿性反转使得原本阻碍油气运移的毛细管力转化为吸附力,从而显著改善流体的运移条件,并形成继承性的优势运移通道,为中、后期油气运移方向的预测提供了重要地质依据^[66]。其次,早期油气充注能够有效抑制后期破坏性成岩作用,对储层物性具有显著的保存效应^[67]。①早期充注的油气占据孔隙空间,增强了岩石的抗压实能力,有效抵御了后期深埋过程中的机械压实;②油气的存在隔绝了地层水与岩石的接触,抑制了胶结等破坏性成岩作用的发生,使早期孔隙得以保存至深埋期^[68]。以塔北地区奥陶系为例,海西晚期储层埋藏普遍较浅,成岩压实作用弱,原生与次生孔隙保存

良好^[69]。伴随该期玉尔吐斯组烃源岩的大量生、排烃,优先排出的有机酸溶蚀了方解石胶结物等易溶组分,进一步扩大了储集空间。此外,早期成藏对盖层封闭性的演化也具有重要意义。古老油气藏自古生代成藏之后,经历了漫长而稳定的地质历史时期,随着盖层不断增厚、地层围压增大,泥岩和页岩等盖层的塑性增强,封闭性逐渐提高,从而有利于油气藏的长期保存。

3 油气藏的改造机制

塔北地区超深层古老油藏自海西晚期主成藏以来,历经约250 Ma的地质演化,其保存过程实质上是与多种潜在破坏性改造作用相抗衡的过程。厘清这些作用的发生机制、触发条件及其对油藏的影响,是揭示古老油藏得以长期保存的关键前提。总体而言,油藏经历的改造作用按其地质背景与主控因素可分为两大类:①与构造抬升和浅埋藏相关的物理-生物改造作

用(如构造调整、生物降解);②与深埋藏和高温环境相关的化学改造作用[如热裂解作用、热化学硫酸盐还原作用(TSR)及气洗作用]。这些改造作用的类型和强度共同决定了油藏的最终相态与规模^[70-71]。

3.1 构造调整与断裂活动

多期构造运动是古老油藏面临的最直接且贯穿其演化始终的改造因素。构造运动可通过区域抬升剥蚀导致盖层失效,或通过改变圈闭形态与溢出点引发油气的再分配或散失,从而对早期油藏构成严重破坏^[72-73]。加里东期与海西早期的强烈抬升直接导致塔北地区加里东期形成的原生油藏被破坏,原油多以固体沥青形式残留^[44,74],这说明稳定埋藏背景对于油藏保存至关重要。而在哈德逊地区,喜马拉雅期的构造挤压导致地层倾向发生反转,促使原油向南侧的新圈闭中运移并重新聚集^[75-76]。此类构造调整虽未造成油气全部散失,但改变了油藏的分布格局。

断裂活动对油气藏的影响具有显著的两面性。

- ①断裂可作为破坏性因素,直接切穿圈闭或盖层,导致油气泄漏。例如,轮南地区海西早期油藏曾因后期断裂活动遭破坏,原油向浅部运移并发生严重降解^[77]。
- ②对于塔北地区现今保存的油藏而言,断裂系统主要

发挥了建设性作用。海西期及更早时期形成的深大走滑断裂系统,构成了沟通寒武系烃源岩与奥陶系储层、促成油气大规模垂向运聚的核心通道^[37]。值得强调的是,海西晚期主成藏后,塔北地区进入以整体沉降为主的相对稳定阶段,未经历大规模的构造抬升与强烈的断裂再活动,这为油藏的长期稳定保存提供了宏观构造背景^[78]。

3.2 浅埋藏阶段的生物降解作用

生物降解是发生在低温(通常 $< 80\text{ }^{\circ}\text{C}$)、近地表或存在好氧菌/硫酸盐还原菌活动条件下的典型蚀变作用。该作用会选择性消耗原油中的正构烷烃等组分,导致原油密度和黏度升高,并形成25-降藿烷及不可分辨复杂混合物(UCM)鼓包等显著的地球化学标志(图7)^[78]。此外,可利用原油中25-降藿烷、甾烷和正构烷烃等生物标志化合物的含量以及金刚烷比值,来定量或半定量评价原油的生物降解程度^[79]。总体而言,生物降解作用会显著劣化油藏的流体品质。

在塔北地区,生物降解作用主要发生于油藏形成后尚未深埋的特定地质历史阶段。海西运动期间,塔北隆起区奥陶系储层一度处于埋深较浅且地温较低($< 70\text{ }^{\circ}\text{C}$),加之局部盖层遭受剥蚀,为生物降解作用创

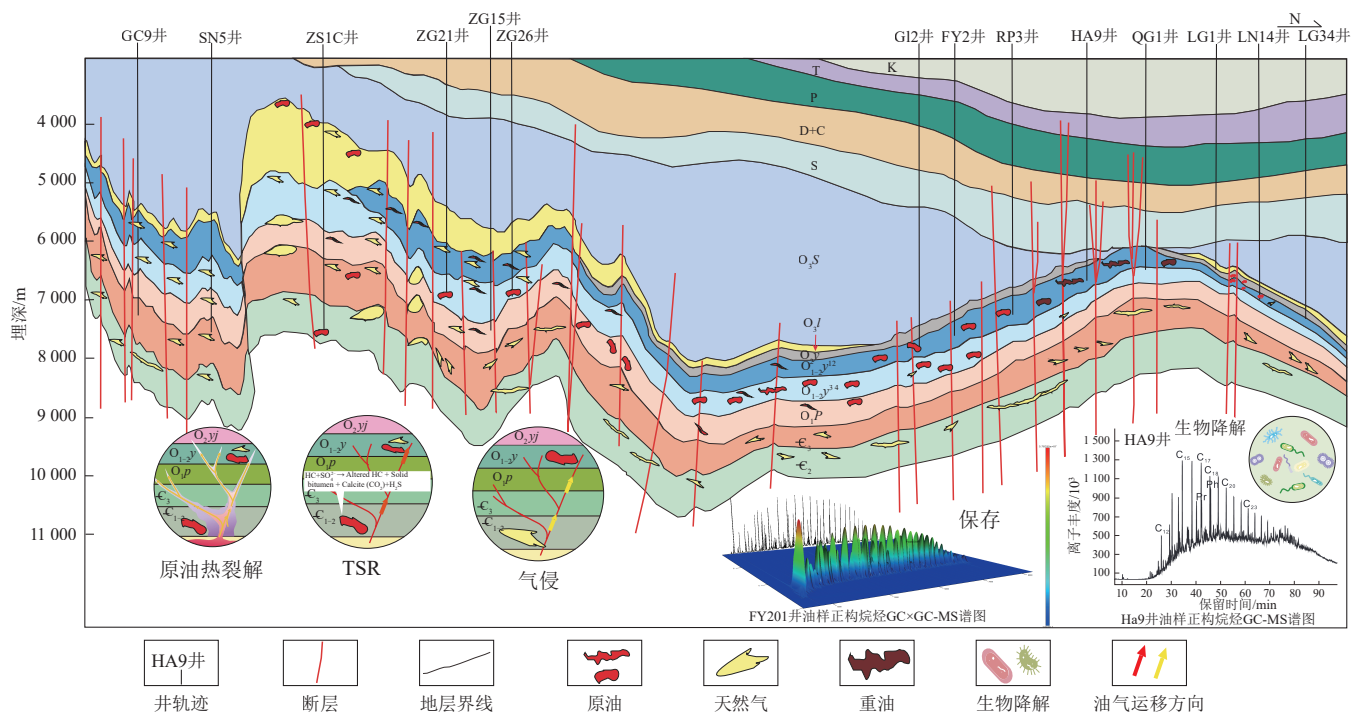


图7 塔里木盆地次生蚀变综合剖面示意图(据文献[78,110]修改)

Fig. 7 Schematic diagram of the composite section showing secondary alteration in the Tarim Basin (modified after references [78,110]) (ϵ_2 为中寒武统; ϵ_3 为上寒武统; O_{2p} 为下奥陶统蓬莱坝组; O_{1-2y}^{3+4} 为中-下奥陶统鹰山组三段和四段; O_{1-2y}^{1+2} 为中-下奥陶统鹰山组一段和二段; O_{2y} 为中奥陶统一间房组; O_{3l} 为上奥陶统良里塔格组; O_{3s} 为上奥陶统桑塔木组; S 为志留系; $D+C$ 为泥盆系+石炭系; P 为二叠系; T 为三叠系; K 为白垩系。)

造了有利条件,导致哈拉哈塘北部等地区的一部分原油发生稠化(如哈9-1井和齐古1井)^[80-81]。然而,对于现今保存完好的工业性油藏(如哈拉哈塘南部、富满和顺北油田等),其原油饱和烃色谱基线平直,正构烷烃分布完整(图7),且在质/荷比 $m/z = 177$ 质量色谱图中未检测出25-降藿烷类化合物,表明其未遭受明显的生物降解作用^[82],这进一步印证了塔北地区主体古老油藏具备优越的保存条件。

3.3 深埋高温环境下的化学蚀变作用

进入深埋阶段,高温引发的化学蚀变成为超深层油藏保存的最大威胁,主要包括热裂解作用和TSR作用^[83-84]。

3.3.1 热裂解作用

原油热裂解是指随埋深增大及热应力增加,原油中的大分子化合物裂解成轻烃组分,生成大量的甲烷和焦沥青,导致超深层高温储层中多以凝析气藏和游离气藏为主^[29]。因此,原油热裂解和TSR作用是超深层古老油藏液态烃保存的主要风险^[85]。

塔里木盆地台盆区海相原油整体保存较好,多数地区未发生明显的热裂解改造。金刚烷具有优异的热稳定性,在原油裂解过程中会不断富集^[79],因此常通过其含量来判断原油裂解程度^[86-87]。研究显示,塔北地区的4-+3-MD(3-甲基双金刚烷+4-甲基双金刚烷)值较低,总体裂解程度不高,其中富满和顺北油田的裂解率为0~24%^[18,88-89];富源和哈拉哈塘油田原油中未检测到乙基金刚烷及硫代金刚烷,表明原油尚未发生大规模裂解^[29,60,78]。

3.3.2 TSR作用

TSR作用是指在高温条件下,硫酸盐与有机物或者烃类发生的氧化-还原反应,生成 H_2S 和 CO_2 的过程^[90-92]。TSR作用对油气藏具有多重影响。①改变油气组分与相态:TSR作用会消耗油气,尤其是重烃(高碳数烃类),因其吉布斯自由能较低而更易发生TSR作用^[93]。②加速原油裂解:TSR作用会显著降低原油的稳定性^[94],促进原生油藏向次生油藏或凝析气藏转化。③改造储层:TSR作用产生的 H_2S 等酸性流体可以溶蚀碳酸盐岩,促进优质储层发育^[94-95]。但也有研究认为其对于储层孔隙度的改善效果有限^[96-97]。TSR作用在富含蒸发岩的超深层碳酸盐岩储层中尤为普遍^[78],通常通过天然气中 H_2S 的含量、金刚烷和硫代金刚烷化合物的相对丰度以及轻烃异构化参数(K_I)来指

示其作用程度^[98-100]。

前人研究结果表明,塔里木盆地原油经TSR作用改造后具有二苯并噻吩/菲(DBT/P)丰度比值高于 $2.0^{[101]}$ 、天然气中 H_2S 含量大于3%^[71]、 K_I 值异常高(可达1.7,常规原油 K_I 为 $1.0^{[102]}$)以及硫代金刚烷丰度高等特征。而富满、顺北、富源以及哈拉哈塘油田的天然气中 H_2S 含量低($<1\%$)^[18]、DBT/P丰度比值低(<1.6)^[97]、 K_I 值接近1.0,且硫代金刚烷相对含量较低。对这些地球化学特征综合分析表明,塔北地区没有或仅存在较微弱的TSR作用^[15,82,89,103]。

3.4 气洗作用

气洗作用是指地下可动气体运移进入相对静止的液相烃类中,导致流体性质和相态发生改变的过程^[104]。当气体大量且持续地进入古油藏时,会剥离原油中的可溶轻质组分^[105],而被剥离的正构烷烃损失量可以指示气洗作用的程度和方向^[78,106]。同时,随着气侵作用的增强,原油的碳同位素组成趋于偏重,且金刚烷含量、气/油比(GOR)及相关成熟度指标均显著升高^[79,107]。该过程促使原油中的轻质组分大量散失、重质组分相对富集甚至沉淀,进而引发原油相态分离,是形成次生凝析油和高蜡油的重要机制之一^[108]。

在新生代快速沉降的地质背景下,受深层原油裂解气自东向西持续充注的影响,塔北轮古东地区早期聚集的油藏遭受了强烈的气洗改造^[108-110]。然而,强烈气洗作用目前仅局限于塔中及塔北东部局部地区。马安来等(2020)指出,顺北地区天然气总体呈现湿气特征且甲烷碳同位素偏轻,表明顺北奥陶系油藏整体未受强烈气洗作用的影响^[18]。地球化学特征显示,富满地区原油的正构烷烃损失量为9.4%~20.0%^[89],显著低于遭受强烈气洗作用的轮古东地区,说明该区仅经历了微弱的气洗作用^[88,103]。相比之下,富源地区未发生明显的天然气充注,因为未遭受到气洗作用的破坏^[29]。

综上所述,塔北超深层古老油藏在漫长的地质演化史上经历了多期、多种改造作用的叠加影响。研究表明,大规模的构造抬升和生物降解等强烈的破坏性改造主要发生于主成藏期之前或成藏后不久;而在主成藏期后,得益于相对稳定的构造背景、持续的深埋过程以及特殊的岩性组合,超深层常见的热裂解、TSR以及气洗等强烈的流体改造作用并未大规模发生。这种“弱改造”的地质背景是液态烃得以在超深层长期保存的先决条件,而控制这一弱改造过程的关键因素,正是下一章将要深入探讨的“保存机制”的核心内容。

4 超长时限油藏的保存机制与模式

基于前述对石油地质特征、成藏期次及改造作用的分析,塔北超深层古老碳酸盐岩油藏能够历经约250 Ma而保存完好,主要得益于3大类机制的共同作用:①优越的封盖与持续埋深的构造背景;②“冷盆”与快速深埋的时-温-压耦合抑制效应;③由此造成的软弱次生改造作用。

4.1 优越的封盖条件与持续埋深的构造背景

稳定且有效的封盖体系是油藏得以保存的静态基础。塔北地区古老油藏自海西晚期成藏之后,进入了相对稳定的持续埋深阶段。在构造相对稳定的含油气盆地中,泥页岩和致密灰岩等均可作为有效盖层^[111-112];且泥岩盖层形成后的大幅度沉降或拗陷可诱发异常高压,进一步提升其封盖能力^[113]。塔北地区奥陶系油藏之上发育巨厚(累计达数百米)的泥岩与泥灰岩区域性盖层,其与深部寒武系膏盐岩以及致密碳酸盐岩共同构成了纵向多级封盖体系,有效避免了古老油藏因断裂活动断穿盖层所造成的油藏破坏。这也是顺北和哈拉哈塘等地区虽经历多期断裂活动,古油藏仍能保持完整的重要原因^[15,37]。

“早期持续浅埋、晚期快速深埋”的埋藏史是油藏免受浅表破坏的动态保障。埋藏史恢复结果表明(图6),海西晚期主成藏后,塔北油藏主体未经历大规模的构造抬升与剥蚀,而是持续沉降深埋。这种相对稳定的构造背景是古老油藏保存至今的关键因素^[17]。该埋藏过程对油藏具有多重保护意义:①使油藏始终处于有效盖层封闭之下,避免了因构造抬升导致的盖层失效、生物降解和氧化水洗等作用。②特定的埋藏史为原油提供了稳定的温-压环境。长期的早期浅埋使油藏在大部分地质历史时期处于地温较低的状态,有效避免了原油的大规模裂解。③早期持续浅埋使烃源岩保持了较低的成熟度与良好的生烃潜力,而晚期快速深埋则促使烃源岩进入大量生油气阶段,至今仍可为超深层油气藏的形成提供雄厚的物质基础^[39]。

4.2 “冷盆”背景与快速深埋的时-温-压耦合抑制效应

4.2.1 “冷盆”背景——原油富集保存的关键

烃类在高温下通常热稳定性较差,深埋增温或岩浆热事件易导致油气发生热裂解和变质。然而,目前

关于原油裂解的门限温度尚存争议,卢双舫等(2002)认为在150℃以上的地层中不应存在液态原油^[114];赵文智等(2006)基于原油生气动力学实验指出,原油约在160℃开始大量裂解生成天然气^[115];Schenk等(1997)提出在地质加热条件下,高蜡油裂解成气的门限温度约为180℃,而海相原油稳定性相对较低,其裂解门限温度约为170℃^[116]。近年来的研究则进一步提出,塔里木盆地液态油的极限保存温度可能高达210℃^[117]。对于塔北地区古老油藏而言,原油的实际裂解门限需结合温度、压力 and 高温驻留时间进行综合判断。

塔里木盆地古地温梯度整体呈现“早热晚冷”的演化特征^[118]。早古生代地温梯度较高(3.2~3.5℃/hm),随后显著下降^[119]。晚古生代受岩浆活动影响,地温梯度再次回升至峰值(3.0~3.2℃/hm),加速了玉尔吐斯组烃源岩的热演化进程;至海西晚期,烃源岩古温度达150~160℃,而储层温度仅为95~100℃^[120],这一温差条件有利于液态烃的保存。自海西晚期油气成藏以来,盆地古地温与大地热流总体持续降低。现今塔北隆起埋深0~5000m的地温梯度约为2.2℃/hm(图8),奥陶系储层平均地层温度为145.1℃^[121],晚期整体表现为“冷盆”特征,储层温度尚未达到原油大量裂解的门限。李丹等(2023)研究发现,塔北隆起的地温梯度整体高于顺北拗陷区,表明基底埋深越大,现今地温梯度越小^[27]。受基底埋深增大及深部碳酸盐岩高热导率的共同影响,顺北地区向深部和超深部延伸时,地温梯度平均降至1.66℃/hm^[120]。这意味着即使在埋深7000m以深的超深层,地层温度仍可能低于原油快速裂解的门限^[122]。马安来等(2020)对顺北地区地温的研究进一步表明,该区奥陶系超深层在埋深8000m处的温度始终未超过170℃,未达到原油裂解的临界温度^[18]。这种优越的温控条件使得顺北地区超深层古老油藏得以良好保存。因此,“冷盆”背景是塔里木盆地超深层原油富集与保存的关键因素^[74]。

4.2.2 快速深埋的时-温-压耦合抑制效应——原油保存至今的核心

超深层古老碳酸盐岩油藏得以保存至今的重要原因,在于其时-温耦合效应不足以引发大规模的裂解,同时高压或超压环境进一步协同抑制了烃类的裂解过程。Zhu等(2012)的动力学模拟与热模拟实验表明,在180℃恒温条件下,51%的海相原油转化为天然气至少需要52.8Ma;而在典型的持续深埋加热条件下(升温速率2℃/Ma),则需要100.0Ma^[80]。Behar和

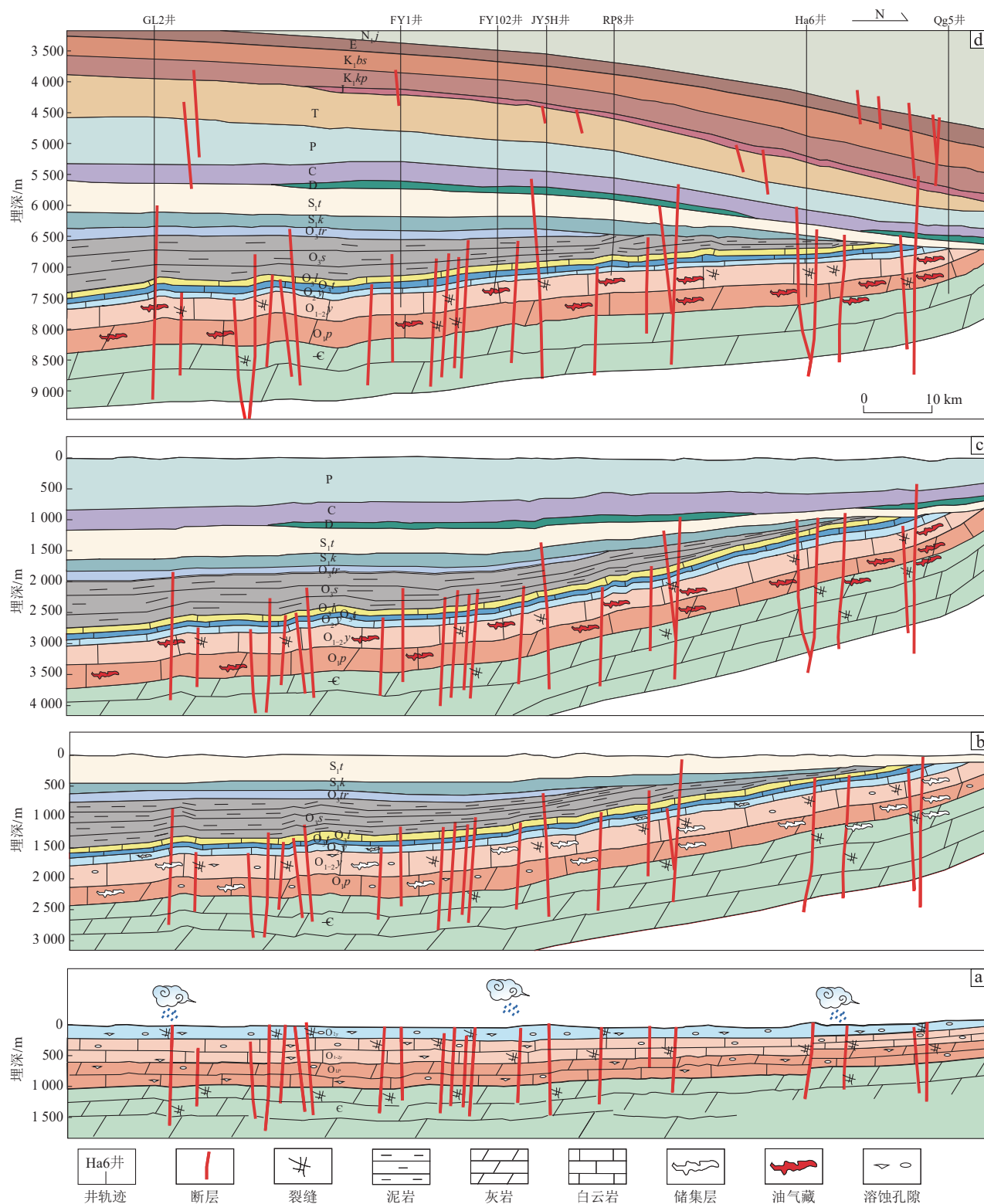


图9 塔北地区古老油藏成藏演化模式示意图(据文献[15]修改)

Fig. 9 Conceptual model of hydrocarbon accumulation and evolution of ancient oil reservoirs in the northern Tarim Basin (modified after reference [15])

a. 加里东早期,奥陶系鹰山组沉积后遭受风化淋滤作用,形成岩溶孔隙储层;b. 加里东晚期,深部岩溶叠加改造,促进岩溶储层进一步发育;c. 海西晚期,来自寒武系烃源岩的原油运移至奥陶系圈闭中聚集成藏;d. 三叠纪以来,盆地持续沉降,油藏埋藏较深且完好保存

(ε为寒武系;O_p为下奥陶统蓬莱坝组;O_{1-2,y}为中-下奥陶统鹰山组;O_{2,y}为中奥陶统一间房组;O_{3,t}为上奥陶统吐木休克组;O_{3,l}为上奥陶统良里塔格组;O_{3,s}为上奥陶统桑塔木组;O_{3,tr}为上奥陶统铁热克阿瓦提组;S_k为下志留统柯坪塔格组;S_t为下志留统塔塔阿尔塔格组;D为泥盆系;C为石炭系;P为二叠系;T为三叠系;J为侏罗系;K_{kp}为下白垩统卡普沙良群;K_{bs}为下白垩统巴什基奇克组;E为古近系;N_j为新近系中新统吉迪克组。)

东部地区。有学者认为,这主要归因于喜马拉雅期塔北地区断层活动微弱,未能切穿深部寒武系蒸发岩盖层,从而阻断了深部气体的向上运移与气洗作用^[138];此外,储层超压环境也有效抑制了深部烃源岩热解气的充注^[129]。

4.4 古老油气藏“早期成藏-持续深埋-低温保存”综合模式

综合前人研究,塔北地区奥陶系古老油藏主要成藏于海西晚期。加里东期造山运动使奥陶系地层抬升出露地表,遭受强烈的风化以及溶蚀作用,形成了优质的缝洞型岩溶储层^[60]。海西早期强烈的构造隆升导致早期充注的原油遭受大规模破坏和生物降解,仅残留少量固体沥青。海西晚期,下寒武统玉尔吐斯组优质烃源岩进入生油高峰,生成的原油沿区域不整合面与断裂系统向奥陶系储层运移,并在具备良好封盖条件的圈闭中聚集成藏,形成了该区的大型原生油藏。成藏后,构造抬升使塔北地区局部构造高部位的油藏遭受生物降解,而南部地区的奥陶系油藏因埋深较深、保存条件优越,原油得以完好保存^[15]。三叠纪以来,塔北地区奥陶系储层总体经历了长期缓慢的埋藏过程,有效规避了生物降解和水洗氧化等次生蚀变作用的破坏。喜马拉雅期晚期(< 5 Ma),塔里木盆地发生快速沉降,导致储层温度急剧上升;然而,由于塔北地区古老油藏处于高温状态的时间较短、区域地温梯度较低,加之高压或超压环境对烃类裂解的耦合抑制作用,原油未发生大规模裂解,油藏至今仍以液态烃为主(图9)^[139]。

5 结论与展望

本研究以塔里木盆地北部地区为例,系统剖析了超深层大型古老碳酸盐岩油藏的地质特征、成藏期次、改造过程与保存条件,揭示了其经历多期构造运动与约250 Ma漫长演化后仍能稳定保存的主控机制,主要取得以下认识:①持续供烃的优质烃源灶、多期岩溶-断裂耦合的大型缝洞型储集体,以及巨厚的多级区域盖层,构成了油藏得以形成的物质基础与先天保障。②“早期持续浅埋-晚期快速深埋”的埋藏史与盆地长期的“冷盆”背景相耦合,因时-温补偿效应微弱,加之高压或超压环境对烃类裂解的协同抑制,有效避免了原油在深埋高温环境下的大规模热裂解。③油藏在主成藏期后经历的构造调整、生物降解、TSR及气洗等次生改造作用均十分微弱,原油地球化学性质保持稳定,

最终实现了“超长时限”的保存。塔里木盆地北部超深层古老油藏的“超长时限”保存,是优越的静态地质要素与独特的动态演化过程时-空匹配、共同作用的结果。这一认识突破了传统“黄金带”理论对液态烃保存深度的限定,为古老克拉通盆地超深层油气勘探提供了新的理论依据。

尽管本研究取得了一定认识,但针对超深层古老碳酸盐岩油藏保存机制这一复杂课题,仍有若干问题有待深入探讨:①多期成藏与多源充注的精细识别。目前对海西晚期主成藏期的认识较为明确,但对早期(加里东期)残余烃与晚期(喜马拉雅期)气源充注的贡献比例、混合效应及其对油藏相态和性质的影响机制,仍需借助更高精度的地球化学与同位素示踪技术加以厘清。②超深层温-压场动态演化与原油裂解动力学过程的高精度定量重建。当前研究多基于盆地尺度的热史模型,未来需结合塔北地区更密集的实测地温数据、流体包裹体、古压力测量、精细的岩石热物性参数以及构造-沉降史资料,建立关键油田尺度的时-温-压演化模型。在此基础上,引入原油裂解动力学参数,开展基于实际温-压路径的正向模拟,并与金刚烷等地球化学指标进行对比验证,从而定量地评价原油裂解动力学过程,以及压力和时-温补偿效应对超深层油藏长期保存的贡献。③超深条件下油气-水-岩相互作用的实验模拟与机理研究。目前对TSR和气洗等作用的认知多源于地球化学反演。未来需开展更接近超深层实际温-压条件下的物理-化学模拟实验,直接揭示这些反应的动力学过程、产物特征及其对储层物性的改造机理。④保存单元边界的动态演化与有效性评价。下一步研究应聚焦于将静态的盖层评价与动态的断裂活动性分析、压力封闭演化相结合,建立保存单元的动态演化模型与有效性评价方法,从而更准确地预测超深层油藏的分布边界与保存状态。

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