

致密油“近源成藏”关键地球化学证据

——以鄂尔多斯盆地延长组近源组合为例

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摘要:致密油“近源成藏”的结论是依据石油在低渗储层中难以长距离侧向运移的储层特征推断得出的, 一直以来缺乏地球化学方面的直接证据。基于对鄂尔多斯盆地三叠系延长组近源组合(长6段—长8₁亚段)中烃源岩特征和油源差异性的分析, 探究了致密油近源成藏的地球化学依据, 并解释了引起近源成藏的原因。研究区近源组合中的石油皆来自于原位长7烃源岩, 即便是邻近区块的油源也存在差异, 石油在致密储层中难以发生大规模的侧向运移。鄂尔多斯盆地长7段烃源岩的生物标志化合物在平面上具有显著差异, 并沿沉积中心呈环带状分布。不同相带生物标志化合物组合差异导致的油源差异, 是前期学者们发现致密油“近源成藏”的根本原因。致密油“近源成藏”改变了之前油源对比全盆地、同一层烃源岩一概而论的观点, 对未来单一盆地中不同类型油气资源量的分区带精细评价具有重要意义。

关键词:近源成藏; 致密油; 油源对比; 延长组; 三叠系; 鄂尔多斯盆地

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Key geochemical evidence of “near-source accumulation” of tight oil:

a case study of near-source assemblage of Triassic Yanchang Formation in Ordos Basin

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Abstract: The conclusion of “near-source accumulation” of tight oil is inferred based on the reservoir characteristics that crude oil is difficult to migrate laterally for a long distance in low-permeability reservoirs, yet there has been no direct geochemical evidence for a long time. Based on the analysis of the characteristics of source rocks and the source differences of oil in the near-source assemblage (Chang 6 member to Chang 8₁ sub-member) of the Triassic Yanchang Formation in the Ordos Basin, this paper explores the geochemical basis of tight oil near-source accumulation and explains its cause. The results show that the crude oil in the near-source assemblage comes from the in-situ Chang 7 source rocks, and even the oil sources in the adjacent blocks are different. It is difficult for crude oil to undergo large-scale lateral migration in a tight reservoir. The biomarker compounds of Chang 7 source rocks in the Ordos Basin have significant differences in the plane and are distributed in a circular belt along the sedimentary center. The oil source difference caused by the combination difference of biomarker

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compounds in different facies zones is the fundamental reason for the predecessors' discovery of "near-source accumulation" of tight oil. The "near-source accumulation" of tight oil has changed the previous view that oil source correlation is a generalization of the whole basin and the source rocks of the same layer, and has important significance for the zoning and fine evaluation of different types of oil and gas resources in a single basin in the future.

Key words: near-source accumulation; tight oil; oil-source correlation; Yanchang Formation; Triassic; Ordos Basin

目前对致密油宏观地质条件和富集规律的研究已经相对成熟,产出了一批具有前瞻性的成果认识^[1-6]。总体上认为致密油具有以下 5 个典型的地质特征:(1)油藏多准连续性分布于烃源岩灶内或构造斜坡区,源储间的压差是主要的成藏动力^[2,7-9];(2)储集层岩性主要包括与烃源岩邻近的致密砂岩和致密灰岩,主要的勘探领域为湖泊碳酸盐岩、浅湖滩坝砂岩、三角洲前缘砂岩和深湖重力流砂岩^[10-15];(3)储层物性极差,储集空间类型多样,发育微纳米级孔喉系统,孔喉连通性差,微裂缝沟通是石油运移和聚集的关键^[16-17];(4)石油充注具有一定的物性下限,只有在达到启动压力梯度后渗流才能发生^[18-20];(5)石油未经大规模长距离运移,以“近源成藏”为特征,源储接触关系对石油运聚至关重要^[21-24]。

以上认识虽然能够体现致密油的整体富集规律,指明致密油的优势富集区,但依然存在若干至今没有清楚的科学问题。其中就包括致密油以“近源成藏”为特征,但此结论是依据石油在低渗储层中难以长距离侧向运移的储层特征推断得出的,并未有地球化学方面的直接证据^[25]。另外,目前进行油源对比时,往往将整个湖盆、同一套源岩作为整体,以寻找纵向上不同层位源岩间地球化学指标的差异,而忽视了同层烃源岩由于平面上相带不一致造成的母源差异性。在以上问题未得到解决之前,很难判断盆地周缘油藏中的石油是来自湖盆中部还是边部烃源岩,也就很难对盆地不同区块的油气资源量进行精确评价。

由于盆地级别油源区的划分直接关系到勘探部署思路的确定,本文选择鄂尔多斯盆地长 7 段烃源岩及邻近(长 6 段和长 8₁亚段)储集层作为研究对象,通过对重点含油区块烃源岩生烃潜力、生烃母质类型和邻近储层石油来源等方面的研究,来初探盆地不同区带致密油的油源差异及成因,为致密油“近源成藏”提供地化方面的直接证据,同时为单一湖盆油气资源的分区分带评价提供新的思路。

1 地质背景

鄂尔多斯盆地是中国的第二大沉积盆地,盆地

总面积约为 $37 \times 10^4 \text{ km}^2$,可供勘探面积达 $10 \times 10^4 \text{ km}^2$ 以上。自 20 世纪 90 年代起,鄂尔多斯盆地一直是国内陆相油气勘探开发的热点地区,目前年产油气当量已突破 $7\,000 \times 10^4 \text{ t}^{[26]}$ 。其中在晚三叠世沉积的延长组是盆地最重要的含油层系之一,由于储层物性较为致密,构造相对平缓,发育的油藏类型主要为低渗透岩性油藏^[22],具有油藏分布面积广、各层位普遍含油的特点(图 1a)。

鄂尔多斯盆地上三叠统延长组自下而上被划分为长 10 段—长 1 段 10 个油层组。长 7 段沉积期为湖盆发育的鼎盛阶段,广泛沉积了富含有机质的半深湖—深湖相泥页岩,构成了盆地中生界最主要的生油岩,湖盆的沉积中心和生烃中心位于姬塬—华池—正宁一带^[25,27-29]。长 8 段和长 6 段致密砂岩储层紧邻长 7 段烃源岩,油源条件好,是低渗透致密油的主要富集层位(图 1b)。

2 典型含油区烃源岩对比评价

同一湖盆的不同区带往往在水体环境、生物类型、物源输入和构造形态等方面存在较大差异,会造成同一层烃源岩在盆地不同地区的沉积厚度、有机质丰度、类型和成熟度具有显著区别,进而造成不同地区的油源具有差异。鄂尔多斯盆地属于大型内陆克拉通盆地,延长组沉积期湖盆范围广,作为鄂尔多斯盆地中生界油藏最主要油源的长 7 烃源岩,其厚度介于 $0 \sim 120 \text{ m}$ 之间^[22,30],在平面上的非均质性较强。在资源量评估和油源精细对比之前,有必要对不同区块长 7 烃源岩的生烃潜力做对比评价。

2.1 有机质丰度

对比分析鄂尔多斯盆地 18 个主要含油区块的 108 块长 7 烃源岩样品的有机碳(TOC)含量,发现 TOC 含量处于 $0.62\% \sim 27.5\%$ 之间,平均为 6.36% ,TOC 含量大于 2.0% 的样品占到 88.9% ,大于 10.0% 的样品占到 14.8% ,有机质丰度高,属于优质烃源岩。但长 7 烃源岩的 TOC 含量在不同区块有明显差异(图 2),华池、合水、白豹地区的 TOC 含量较高,平均值达到 10% 以上;上里塬、环县、胡尖山、

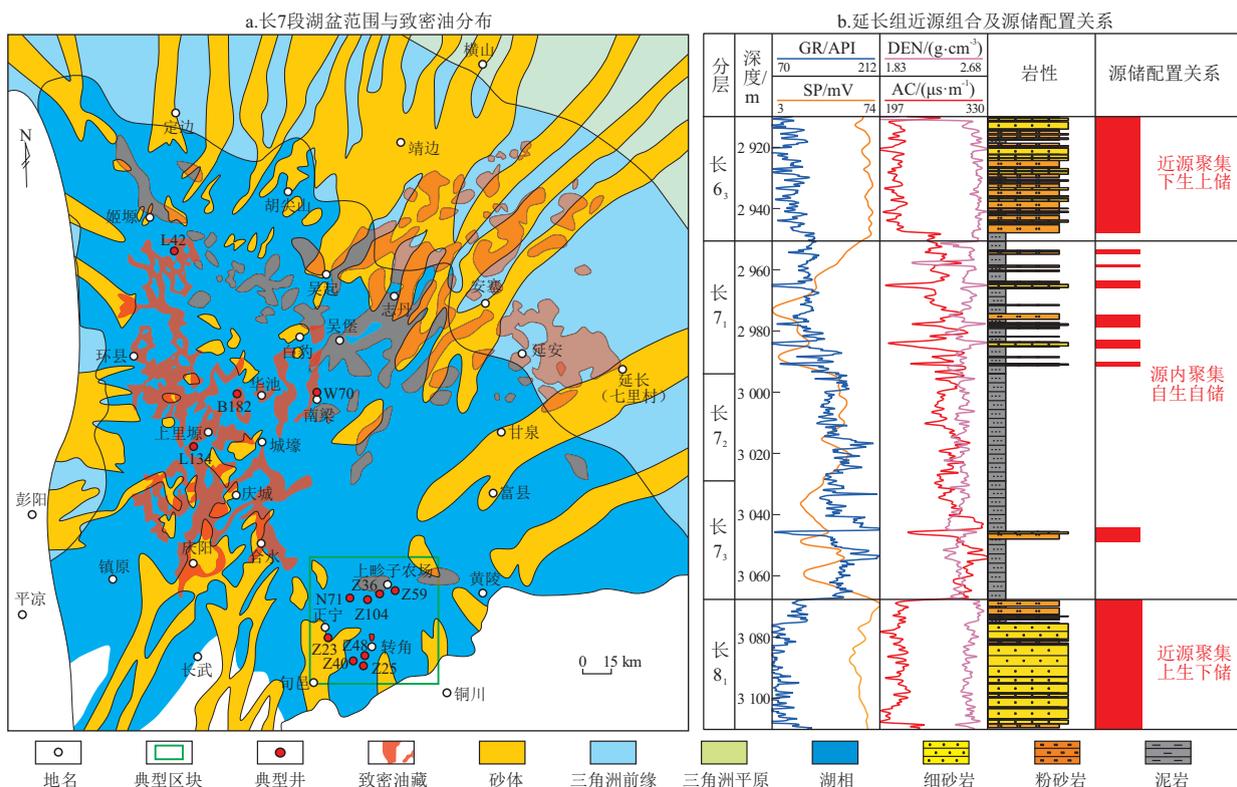


图1 鄂尔多斯盆地三叠系延长组近源组合致密油的平面分布及源储配置关系

Fig.1 Tight oil plane distribution and source-reservoir configuration relationship of near-source assemblage of Triassic Yanchang Formation in Ordos Basin

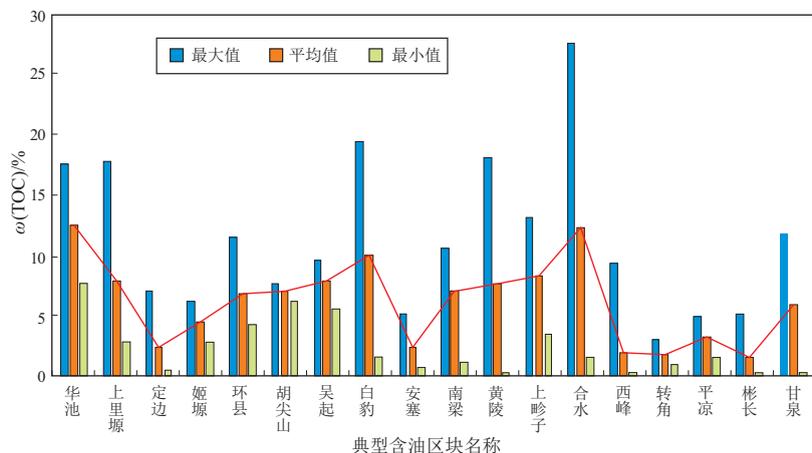


图2 鄂尔多斯盆地三叠系延长组 18 个主要含油区块长 7 烃源岩的 TOC 值统计直方图

Fig.2 Statistical histogram of TOC values of Triassic Chang 7 source rocks in 18 main oil-bearing blocks of Ordos Basin

吴起、南梁、黄陵、上矇子农场和甘泉地区的 TOC 含量中等,平均值介于 5%~10%;而姬塬、定边、安塞、西峰、转角、平凉和彬长地区的 TOC 含量较低,平均值处于 5% 之下。对应于各区块在湖盆的位置(图 1a),长 7 烃源岩的 TOC 含量有从湖盆中部向边部减小的总体趋势。

2.2 有机质类型

对鄂尔多斯盆地 18 个主要含油区块共 139 块长 7 烃源岩样品的干酪根显微组分特征统计

(图 3)表明,腐泥组在长 7 烃源岩中占有绝对的优势,壳质组次之,镜质组和惰质组的含量较少。长 7 烃源岩的有机质类型主要为 I 型,含少量 II₁型,不同地区略有差异。相较而言,处于湖盆中部的华池、上里塬、白豹、南梁、合水、上矇子农场、黄陵地区长 7 烃源岩的腐泥组含量较高,而处于湖盆边部的胡尖山、环县、定边、志丹、吴起、甘泉、安塞和彬长等地区长 7 烃源岩中含更多的壳质组。湖盆中部和边部干酪根显微组分的差异表明,长 7 湖盆沉

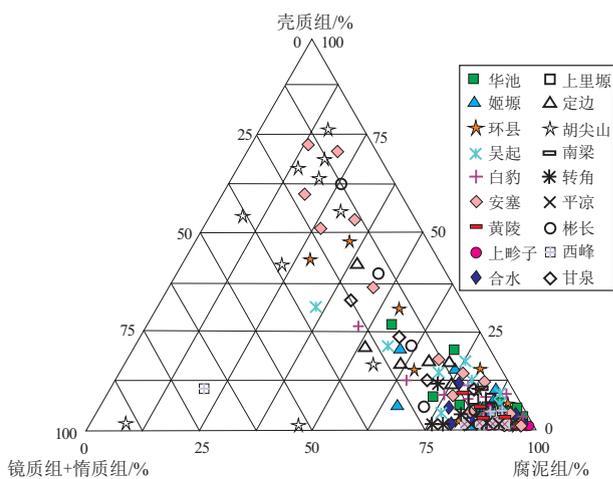


图3 鄂尔多斯盆地三叠系延长组 18 个主要含油区块长 7 段烃源岩的干酪根显微组分三元图

Fig.3 Ternary diagram of kerogen macerals of Triassic Chang 7 source rock in 18 main oil-bearing blocks of Ordos Basin

积中心是湖生藻类生物主导的生源类型^[31],而湖盆边部的生源类型中有一定高等植物的参与。

2.3 有机质成熟度

统计鄂尔多斯盆地 18 个主要含油区块 102 块长 7 烃源岩样品的镜质体反射率(R_o)数据(图 4)表明,长 7 烃源岩的 R_o 为 0.45%~1.27%,平均值为 0.75%。其中, $R_o > 0.7%$ 的样品占 66.3%, $R_o > 0.5%$ 的样品占 86.3%,指示长 7 烃源岩处在低成熟—成熟阶段。从分区统计结果来看,姬塬、吴起、甘泉地区烃源岩的成熟度最高,平均 $R_o > 0.9%$;上里塬、环县、白豹地区烃源岩的成熟度次之,平均 R_o 为 0.8%~0.9%;华池、定边、胡尖山、南梁、上矇子农场和西峰地区烃源岩成熟度较高,平均 R_o 为 0.7%~0.8%;黄陵、合水、转角地区成熟度较低,平均 R_o 为 0.6%~0.7%;而安塞、平凉、彬长地区烃源岩还未

达到成熟,多数 $R_o < 0.5%$ 。对应于各区块在湖盆的位置(图 1a),盆地边部长 7 烃源岩的成熟度整体上较盆地中部低,而湖盆内部长 7 烃源岩成熟度有自东北向西南减小的趋势。

3 致密油近源成藏的证据

鄂尔多斯盆地延长组近源组合中的石油主要生成于长 7 烃源岩已成不争的事实^[27,32-38],所以在盆地尺度上进行油源对比已经没有现实的意义。上文研究表明,盆地中不同区块长 7 烃源岩在厚度、丰度、有机质类型、成熟度方面存在差异,这势必造成不同地区源岩及其产物特征存在差异。若致密油服从近源成藏,则说明石油在砂体中侧向迁移的距离有限,不同区块石油的生物标志化合物特征与同区块烃源岩相似,而与邻区存在差异。

3.1 典型区块油源差异性

为了探讨上述问题,选取盆地南缘的上矇子农场和转角这 2 个邻近区块做油源对比分析。从岩石抽提物的 GC-MS 分析结果可以看出,2 个区块烃源岩和石油的生物标志化合物特征存在一定差异。上矇子农场区块石油和烃源岩的 $Pr/Ph < 1$, $\alpha\alpha\alpha-20R$ 规则甾烷中 C_{27} 和 C_{29} 基本持平,藿烷分布以 $Ts/Tm > 1$ 和 $C_{30}H/C_{30}DiaH < 10$ 为特征(表 1,图 5a 和 c)。转角区块石油和烃源岩的 Pr/Ph 也小于 1,但 $\alpha\alpha\alpha-20R$ 规则甾烷中明显含更高的 C_{29} ,藿烷分布以 $Ts/Tm < 1$ 和 $C_{30}H/C_{30}DiaH > 10$ 为特征(表 1,图 5b 和 d)。分析认为,上矇子农场和转角 2 个区块虽然在平面上邻近,但石油皆源于本地烃源岩,并未经过规模性侧向运移。

与鄂尔多斯盆地中部的华池、姬塬、南梁和上里塬等区块长 7 烃源岩的生物标志化合物特征进

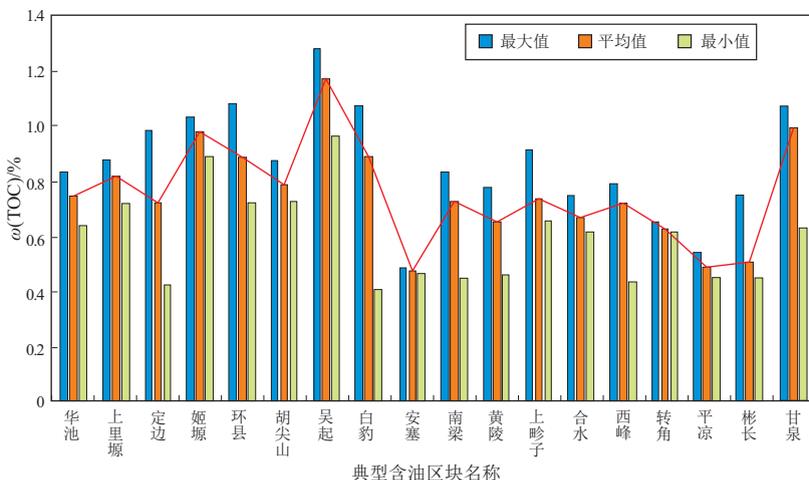


图4 鄂尔多斯盆地三叠系延长组 18 个主要含油区块长 7 烃源岩的镜质体反射率统计直方图

Fig.4 Statistical histogram of R_o values of Triassic Chang 7 source rock in 18 main oil-bearing blocks of Ordos Basin

表 1 鄂尔多斯盆地上曈子农场和转角区块三叠系延长组近源组合中
 烃源岩和储层抽提物的生物标志物化物特征

Table 1 Biomarker characteristics of source rock and reservoir extracts in near-source assemblage
 of Triassic Yanchang Formation in Shangzhenzi farm and Zhuanjiao block, Ordos Basin

区块	层位	井号	深度/m	Pr/Ph	C ₂₇ /C ₂₉	Ts/Tm	C ₃₀ H/C ₃₀ DiaH
上曈子 农场	长 7	Z59	1 263.20	0.62	0.72	1.44	8.15
		N71	1 651.40	0.75	0.82	1.15	5.77
	长 6	Z36	1 188.15	0.99	0.89	1.13	8.74
		Z59	773.70	0.76	0.74	1.17	5.10
转角	长 7	Z104	1 587.30	0.73	0.61	1.76	6.69
		Z25	553.20	0.93	0.53	0.36	12.31
	长 8	Z40	1 275.00	0.97	0.61	0.62	10.16
		Z23	1 253.90	0.93	0.68	0.80	10.62
		Z48	1 270.20	0.93	0.69	0.50	13.00

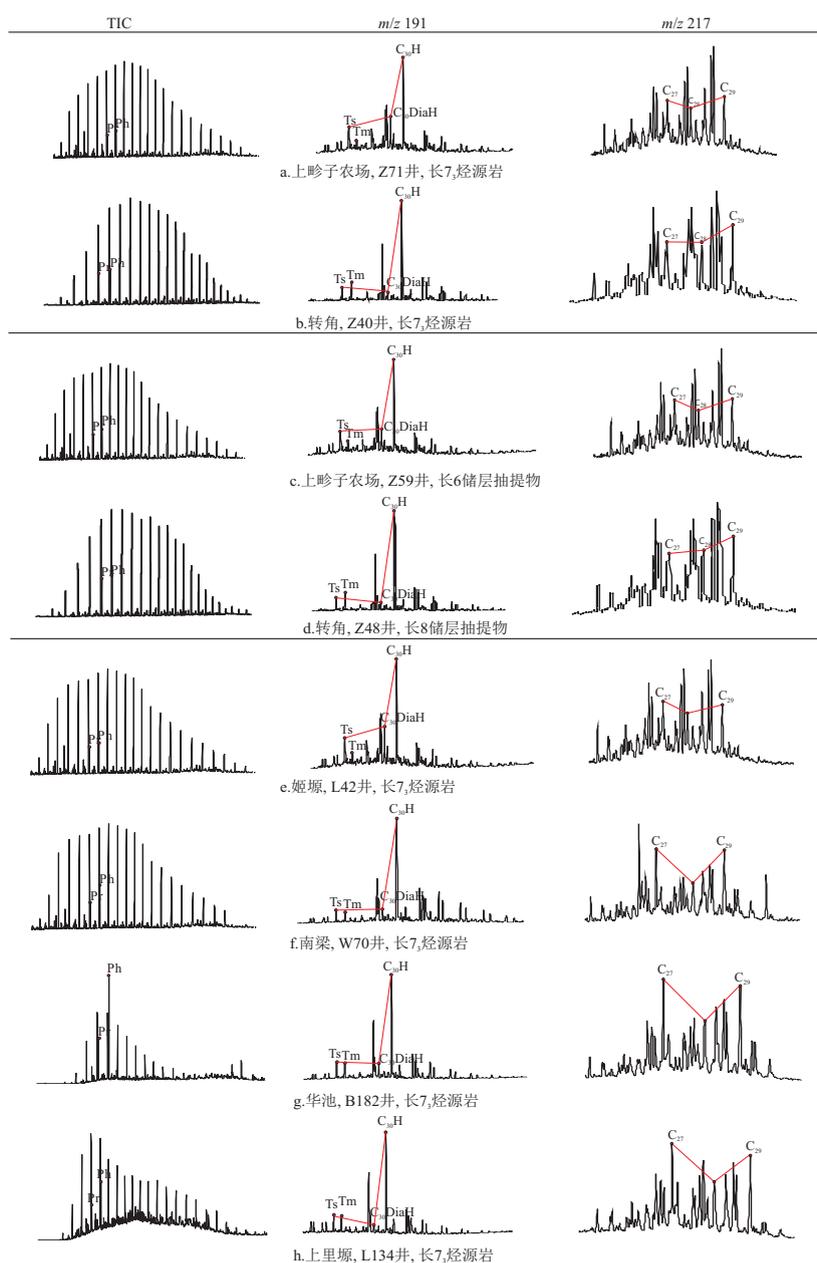


图 5 鄂尔多斯盆地典型区块三叠系延长组近源组合中烃源岩和储层抽提物的 GC-MS 谱图
 Fig.5 GC-MS spectrum of source rock and reservoir extracts in near-source assemblage
 of Triassic Yanchang Formation in typical blocks of Ordos Basin

行对比,发现盆地南缘生烃母质特征与盆地中部地区也有区别。湖盆中部烃源岩皆以 $Pr/Ph < 1$ 和规则甾烷 $C_{27}/C_{29} > 1$ 为特征(图 5e-h),指示还原和以水生藻类为主的深湖相沉积环境,这与上矚子农场区块规则甾烷以 C_{29} 为主峰,含大量陆源高等植物的生源组合不同^[39-40]。上述差异说明,即便是更靠近湖盆中部的上矚子农场区块,其石油也并非源于湖盆中部的深湖相烃源岩。从湖盆南缘到湖盆中部,不同区带油源皆不一样。

3.2 盆地级别油源差异性

为了深入认识鄂尔多斯盆地不同区带油源的差异性,在吸收前人成果的基础上,对 18 个主要含油区的烃源岩和近源储层抽提物进行生物标志化合物特征分析。从统计结果来看(图 6),位于湖盆中部的华池、南梁、上里塬和姬塬区块生烃母质以 C_{27} 甾烷为主, $Pr/Ph < 1$, 指示还原的深水沉积环境;位于湖盆边部的黄陵、定边、环县、甘泉、西峰、吴起区块 C_{29} 甾烷占优势, $Pr/Ph > 1$, 指示富氧的浅水沉积环境;合水、转角、上矚子农场、白豹区块 C_{29} 甾烷占优势, $Pr/Ph < 1$, 指示靠近湖盆中部、含大量陆源输入的过渡性沉积环境。

从甾烷特征来看(图 7),鄂尔多斯盆地延长组近源组合中生烃母质的 Ts/Tm 分布范围较广,对照不同区块长 7 烃源岩的成熟度(图 4), Ts/Tm 高值区也正是烃源岩 R_o 较高的区块,说明 Ts/Tm 是指示有机质成熟度的有效指标,与沉积环境关系甚微。从 $C_{30}H/C_{30}Diah$ 和 Ts/Tm 的相关性来看(图 7), Ts/Tm 与 $C_{30}H/C_{30}Diah$ 呈反比,在 $Ts/Tm < 2$ 之前, $C_{30}H/C_{30}Diah$ 随 Ts/Tm 的增加而迅速减小;而在 $Ts/Tm > 2$ 之后, $C_{30}H/C_{30}Diah$ 随 Ts/Tm 的增加几乎不再发生变化,指示相对于 $C_{30}Diah$, $C_{30}H$

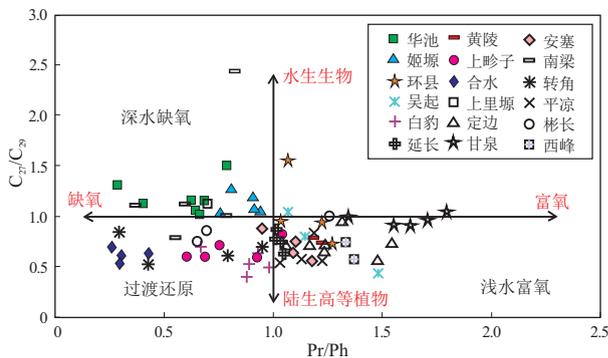


图 6 鄂尔多斯盆地 18 个主要含油区块三叠系延长组近源组合中岩石抽提物的甾烷 C_{27}/C_{29} 和 Pr/Ph 交会图

Fig.6 Cross plots of sterane C_{27}/C_{29} and Pr/Ph of rock extracts in near-source assemblage of Triassic Yanchang Formation in 18 main oil-bearing blocks of Ordos Basin

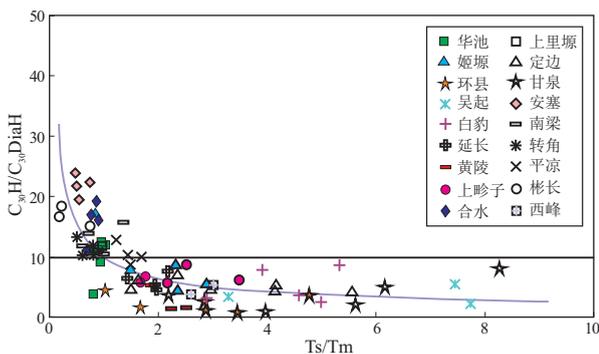


图 7 鄂尔多斯盆地 18 个主要含油区块三叠系延长组近源组合岩石抽提物的 $C_{30}H/C_{30}Diah$ 和 Ts/Tm 交会图

Fig.7 Cross plots of $C_{30}H/C_{30}Diah$ and Ts/Tm of rock extracts in near-source assemblage of Triassic Yanchang Formation in 18 main oil-bearing blocks of Ordos Basin

的热稳定性较差,这与文献[45-46]的研究结论一致。鄂尔多斯盆地延长组近源组合中 $C_{30}Diah$ 丰度与处于湖盆的位置之间没有绝对的相关性,说明 $C_{30}Diah$ 并非与偏氧化和陆源黏土催化直接相关^[47-48],而与生烃母质成熟度的关系更大^[49-51],高的 $C_{30}H/C_{30}Diah$ 代表了低熟烃源岩的特征。

依据上述认识,选择 $C_{30}H/C_{30}Diah$ 、规则甾烷 C_{27}/C_{29} 和 Pr/Ph 三组生物标志化合物指标,对鄂尔多斯盆地主要含油区的生烃母质类型进行划分。从划分结果可以看出(图 8),华池、上里塬和姬塬等地区有机质发育在贫氧环境,目前已达到成熟,指示烃源岩形成于相对深水区;定边、吴起、环县、西峰、上矚子农场、黄陵、甘泉和延长等地区的有机

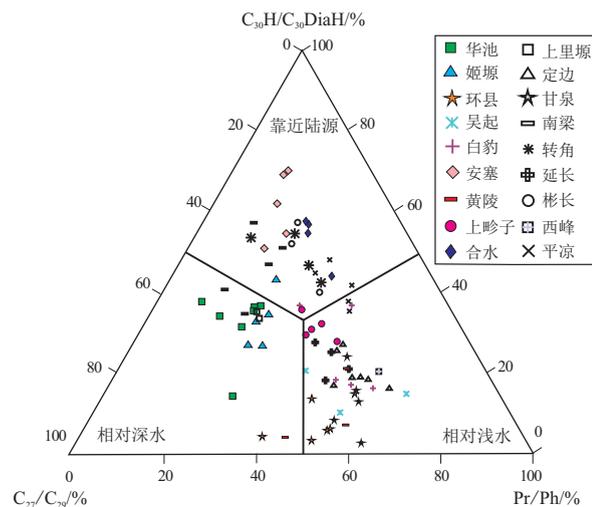


图 8 鄂尔多斯盆地 18 个主要含油区块三叠系延长组近源组合岩石抽提物的

$C_{30}H/C_{30}Diah$ 、规则甾烷 C_{27}/C_{29} 和 Pr/Ph 三元图

Fig.8 Ternary diagram of $C_{30}H/C_{30}Diah$, regular sterane C_{27}/C_{29} and Pr/Ph of rock extracts in near-source assemblage of Triassic Yanchang Formation in 18 main oil-bearing blocks of Ordos Basin

质发育在偏氧化的环境,目前也已达到成熟,指示烃源岩形成于相对浅水区;而安塞、南梁、合水、转角、彬长和平凉等地区的有机质发育在混合相环境,目前还处于低熟阶段,指示烃源岩形成于靠近陆源区。

以上结果表明,不同区带由于生烃母质类型和成熟度的差异,油源并不完全一致。从储集层的角度,盆地边部由于更靠近物源,不论在砂体侧向连续性或储层物性方面都要优于湖盆中部;盆地中部烃源岩生成的产物并未大规模运移至盆地边部储层中富集,至于湖盆中部砂体更不具备石油长距离侧向运聚的客观条件,合理推断可得致密油在全盆地皆服从近源成藏的规律。

4 近源成藏地球化学依据及启示

4.1 致密油近源成藏的地球化学依据

基于上述认识,将相同生物标志化合物的油区归为一类,可见鄂尔多斯盆地延长组近源组合中相

同类型的生物标志化合物组合大致上呈环带状分布(图9)。盆地长7烃源岩沉积时期,湖盆经历了延长组沉积期最大规模的湖侵,湖泊沉积范围大,不同区带烃源岩特征存在微小差异,尤其是湖盆沉积中心和湖盆边缘,烃源岩的沉积环境、成熟度和陆源输入差异较大。不同沉积相带烃源岩沉积环境的差异,必然导致不同相带烃源岩生物标志化合物特征也存在差异,进而造就了相邻区块油源的差异性。前人研究提出的鄂尔多斯盆地西北缘姬塬东西部长6油藏的油源不一致^[52],东部七里村油田长6石油与相邻的志丹和富县地区不同源^[25],西南缘的彭阳地区石油并非来自湖盆中部的厚层烃源岩^[53]等“近源成藏”的地球化学证据,皆是由于沉积环境差异导致的生物标志化合物差异造成的。

4.2 致密油近源成藏的启示

综上,石油在致密储层中发生远距离的侧向运聚是相当困难的,致密油服从近源成藏,这样的定

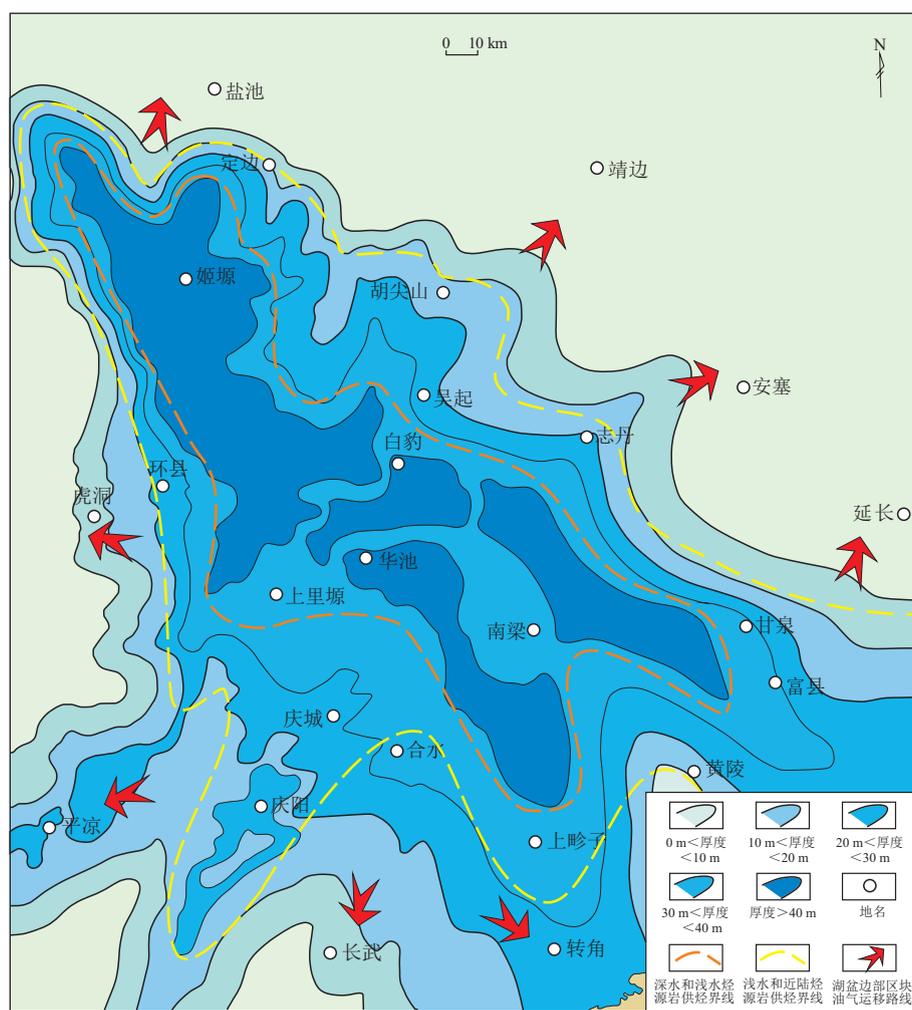


图9 鄂尔多斯盆地三叠系长7烃源岩平面展布及油源分区带特征

Fig.9 Plane distribution of Triassic Chang 7 source rocks and oil-source zoning characteristics in Ordos Basin

调具有以下几个方面的现实意义:(1)因为油源具有分区分带性,所以可根据油源分界线对单一盆地资源量进行分区分带精细评估,这对同一盆地不同区带致密油乃至页岩油的资源量评价具有重要指导意义;(2)由于近源致密油未经长距离侧向运移,盆地周缘远源油藏多是由盆地边部烃源岩供烃,或是由盆地中部烃源岩生成的石油,通过断裂垂向输导相当长的距离后沿着浅层优质砂体侧向运聚而成;(3)常规油气藏规模主要受盆地边部烃源岩的供烃能力控制,湖盆烃源岩之内,尤其是滞留在近源组合中的油气资源量极其巨大,可能远超前期传统认知。

5 结论

(1)鄂尔多斯盆地长 7 烃源岩的沉积厚度、有机质丰度、类型和成熟度在不同区块具有显著区别,造成不同区带生烃母质和生物标志化合物存在差异。选择 $C_{30}H/C_{30}DiaH$ 、规则甾烷 C_{27}/C_{29} 和 Pr/Ph 三组生物标志化合物指标,可将鄂尔多斯盆地主要含油区的生烃母质类型划分为相对深水区、相对浅水区和靠近陆源区三类。

(2)鄂尔多斯盆地延长组近源组合中相同类型的生物标志化合物组合大致上沿沉积中心呈环带状分布。不同沉积相带烃源岩沉积环境的差异,导致烃源岩生物标志化合物特征的差异,进而造就了相邻区块油源的差异性。前人提出的鄂尔多斯盆地致密油“近源成藏”的地化证据,皆是由于沉积环境差异导致的生物标志化合物差异造成的。

(3)致密油服从“近源成藏”,改变了之前油源对比全盆地、同一层烃源岩一概而论的观点,在单一盆地资源量分区分带精细评估、远源油藏运聚体系重新认识、常规与非常规油气藏资源分配等方面具有现实的启示意义。

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