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渭河盆地新发现原油的特征及其油气地质意义

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摘要:渭河盆地地热井中意外发现有石油产出,打破了该盆地无油的历史定论。为了认识该原油的特征及其油气地质意义,对采集的地热井原油的物性、族组分含量、饱和烃含量、甾烷与萜烷组成、饱和烃单体烃碳同位素组成进行了系统分析。分析表明,原油以饱和烃为主、芳香烃和沥青质次之,胶质含量最低,属于正常含蜡、低硫、轻胶质原油。饱和烃色谱呈双峰型,主峰为 C_{15} 和 C_{22},*CPI* 和 *OEP* 值分别为 0.93 和 0.90。原油母质成熟度较高且主要来自浮游水生生物和少量高等植物,并有藻类有机质的贡献。正构烷烃中低碳数(C_{14}—C_{22})的碳同位素值随碳数增加而从 -27.1‰降低到 -30.3‰;当碳数高于 C_{22} 后,碳同位素值在 -29.3‰和 -30.4‰之间变化;姥鲛烷(Pr)和植烷(Ph)的碳同位素值重,分别为 -26.1‰和 -24.9‰。相对较高的伽马蜡烷含量表明了原油母质形成于较高盐度的水体中。通过邻区对比发现,该原油特征与鄂尔多斯盆地二叠系、三叠系延长组、侏罗系等已知产油层位的原油差别较大,显示出明显的地球化学与成因的特殊性。新发现原油表明渭河盆地应具有尚未发现的生烃源岩,对渭河盆地的油气勘探具有重要的指导意义,同时也可为鄂尔多斯周缘盆地新层系油气调查提供借鉴。

关键词:生物标志物;地球化学;原油;地热井;渭河盆地
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Characteristics of newly discovered crude oil in the Weihe Basin and its petroleum geological significance

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Abstract: The unexpected production of oil from the geothermal wells in the Weihe Basin breaks the conclusion of history that there is no oil distributed in the region. We made a systematic study of the crude oil in terms of its physical property, group composition, content of saturated hydrocarbon, composition of sterane and terpane, as well as carbon isotope composition of saturated hydrocarbon monomer, with a view to explore the characteristics of crude oil and its petroleum geological significance for the basin. The results show that the crude oil compositions are predominated by saturated hydrocarbons, followed by arene and asphaltene, and with the colloid coming last, thus it belongs to a kind of low-sulfur crude oil with light colloid and normal content of wax. Its saturated hydrocarbon chromatogram is bimodal, with the main peaks corresponding to C_{15} and C_{22}, and the *CPI* and *OEP* values are 0.93 and 0.90 respectively. The organic matters of the crude oil are high in maturity, and mainly sourced from planktons, followed by certain higher plants and algaes. The carbon isotope value of low n-alkanes (C_{14} - C_{22}) decreases from -27.1‰ to -30.3‰ along with the increase of carbon number. When the carbon number is higher than C_{22}, the carbon isotope value varies between -29.3‰ and -30.4 ‰. In addition, the carbon isotope values of pristane (Pr) and phytane (Ph) are relatively heavy at 26.1‰ and 24.9‰, respectively. Higher content of gammacerane indicates that the organic matters are produced in an environment of higher salinity. Compared with the adjacent areas, the crude oil has a great difference with that from the Permian, the Triassic Yanchang Formation and the Jurassic in the Ordos Basin in terms of geochemistry and origin. The newly discovered crude oil

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indicates that the Weihe Basin may still have source rocks undiscovered, which is of great significance to guide the petroleum exploration of the basin. At the same time, it is also of referential meaning for oil and gas survey in the unexplored sequences in Ordos Basin.

Key words: biomarker, geochemistry, crude oil, geothermal well, Weihe Basin

渭河盆地位于陕西省中部,地处秦岭造山带与鄂尔多斯盆地之间(图 1)。20 世纪 60—70 年代,原地质部第三石油普查勘探大队以新生界为目的层对渭河盆地开展过石油普查工作,但由于巨厚的新生界以红层为主,有机质丰度和成熟度低,缺乏有效烃源岩而停止石油普查。近年来渭南市为了推动低碳经济发展,加快地热资源的开发利用,陕西金奥能源开发有限责任公司(渭河能源公司)在渭南地区实施了 15 口地热探井。地热井以蓝田 - 灞河组、高陵群热储层为主要目的层,地热开采中自喷压力高,温度高,水量较大。在地热水开采过程中发现了含有较高浓度的伴生氦气和甲烷气资源。由于前人普遍认为渭河盆地不具备石油地质条件,地热井录井项目简单,不取心,没能发现石油显示,也未曾想到地热井中有石油。但高温的地热水经供暖后,发现有石油在回水管线中逐渐析出,并粘附于管壁上,经年累月的积累最终导致管线堵塞破裂,见到了“油饼”,才使人们想到地热水中有石油。通过对 2 口井安装井口油水分离装置,首次在渭河盆地获得了新生代地层产出的原油数百千克(图 2)。原油经有机地球化学分析,表明其与鄂尔多斯盆地已发现的延长组、侏罗系、二叠系等层位的原油都有较大差别,应有其特殊的成因和来源。

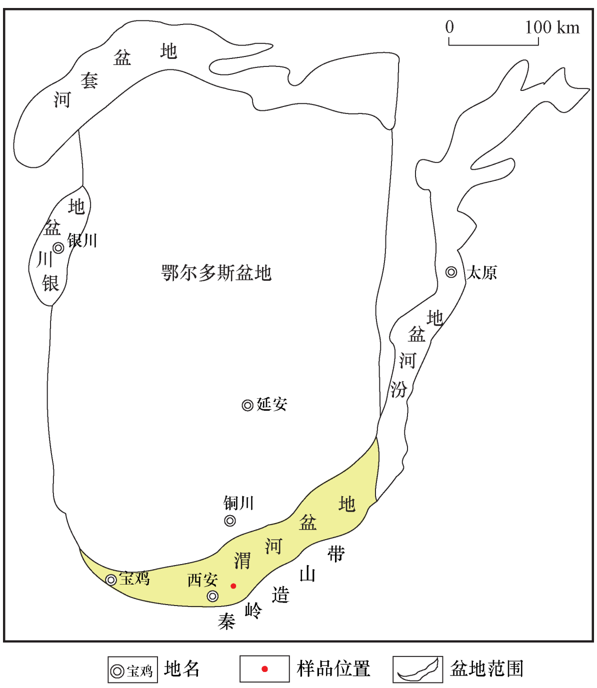

图 1　渭河盆地大地构造位置

Fig. 1　Tectonic location of the Weihe Basin

1　原油物性与族组成特征

根据原油样品的物性和族组分分析结果,原油密度和粘度分别为 0.82 g/cm^3 和 6.42 mPa·s,原油饱和烃、芳香烃、非烃和沥青质的相对百分含量分别为 82.2%、7.7%、3.8% 和 6.3%,与鄂尔多斯盆地三叠系及侏罗系原油族组成有明显差异(表 1),饱和烃含量明显较高,饱/芳比值高达 10.68。另外,原油的含蜡量和含硫量分别为 14.89% 和 0.032 3%。所以,该原油属于正常、含蜡、低硫的轻胶质原油[1-2]。原油的初馏点温度为 123.9 ℃,随温度升高,初馏馏分含量增加,50% 出馏馏分对应的温度为 317.4 ℃(图 3)。

图 2　渭河盆地地热井产出的沥青(a)和原油(b)照片

Fig. 2　Photos of asphalt sample (a) and crude oil sample (b) from geothermal wells in the Weihe Basin

表 1　渭河盆地原油与鄂尔多斯盆地不同层位原油族组分对比

Table 1　Comparison of group compositions for crude oil at different horizons in the Weihe and Ordos Basins

样品	族组分含量/%				饱/芳
	饱和烃	芳香	非烃	沥青质	
鄂尔多斯盆地长武地区延长组原油[3]	53.88	18.13	15.76	12.23	2.97
鄂尔多斯盆地天环坳陷南段侏罗系原油及油砂抽提物[4]	26.36 ~ 65.27	13.33 ~ 27.37	11.98 ~ 50.91		1.60 ~ 4.10
渭河盆地原油	82.20	7.70	3.80	6.30	10.68

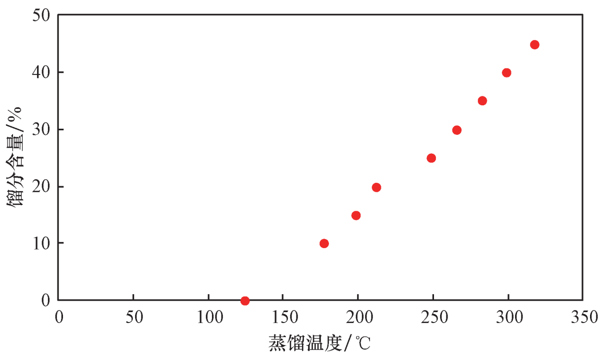

图3　渭河盆地原油馏分分馏与温度的关系

Fig. 3　Relationship between distillation temperatures and fraction contents of crude oil samples in the Weihe Basin

2　原油饱和烃特征

原油饱和烃气相色谱图(图4)显示,渭河盆地原油正构烷烃碳数从C_{10}到C_{38},总体呈双峰型,主峰为nC_{22},次主峰为nC_{15},这区别于鄂尔多斯盆地各层原油的单峰型特征。原油的*CPI*和*OEP*值分别为0.93和0.90,表明原油是成熟的。$\sum nC_{21-}/\sum n-C_{22+}$和$(nC_{21}+nC_{22})/(nC_{28}+nC_{29})$分别为1.05和1.55;$Pr/Ph$,$Pr/nC_{17}$和$Ph/nC_{18}$分别为0.82,0.56和0.59。$Pr/nC_{17}$和$Ph/nC_{18}$关系图(图5)显示,其母质应该有藻类等水生生物的贡献,总体显示原油的母质形成于弱还原的沉积环境[5-8]。

3　原油甾烷与萜烷特征

在渭河盆地原油甾烷(m/z 217)组成中,孕甾烷、$20SC_{27}$重排甾烷与$20RC_{27}$重排甾烷相对含量明显较鄂尔多斯盆地三叠系及侏罗系原油高(图6),其孕甾烷与$C_{27}+C_{28}+C_{29}$甾烷比值为0.21,$(20S+20R)C_{27}$重排甾烷与$\sum(C_{27}+C_{28}+C_{29})$甾烷比值为1.0。$C_{27}$,$C_{28}$与$C_{29}$规则甾烷呈反“L”型分布,与鄂尔多斯盆地侏罗系原油的“L”型特征差异明显,C_{27}与C_{29}甾烷比值和C_{27}与C_{28}甾烷比值分别为0.46和0.96。C_{27},C_{28}和C_{29}规则甾烷组成三角图(图7)显示,渭河盆地原油母质主要来自浮游水生生物和少量高等植物,高等植物对其贡献比鄂尔多斯盆地延长组原油高[10-11]。此外,原油含有少量4-甲基甾烷,这预示了其母质形成于具有一定盐度的沉积环境,并且藻类有机质对母质也有所贡献(图6)。

C_{29}甾烷异构体中$20S/(20S+20R)\alpha\alpha\alpha C_{29}$,甾烷和,$\beta\beta/(\beta\beta+\alpha\alpha)20RC_{29}$甾烷是生标物中重要的成熟

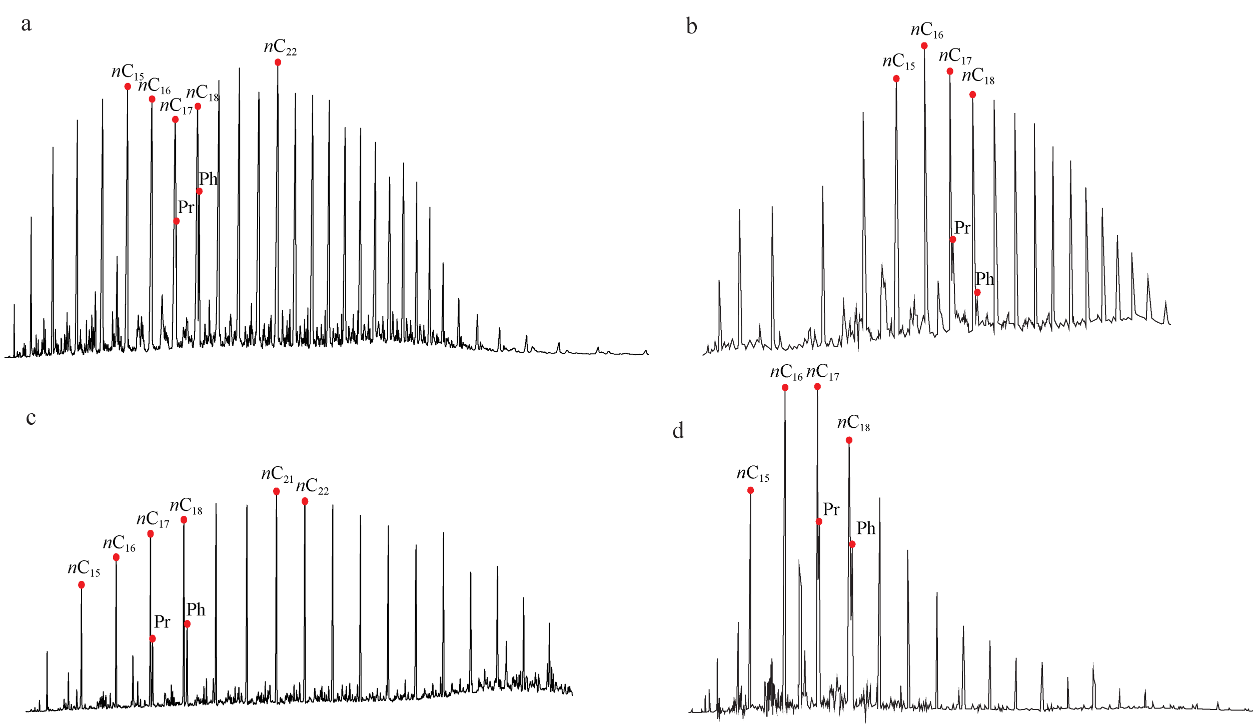

图4　渭河盆地与鄂尔多斯盆地原油饱和烃气相色谱(GC)

Fig. 4　Gas chromatogram of the saturated fraction of crude oil samples in the Weihe and Ordos Basin

a. 渭河盆地原油;b. 鄂尔多斯盆地北部二叠系石盒子组原油[9];c. 鄂尔多斯盆地西峰地区三叠系延长组原油;

d. 鄂尔多斯盆地天环坳陷南段侏罗系原油[4]

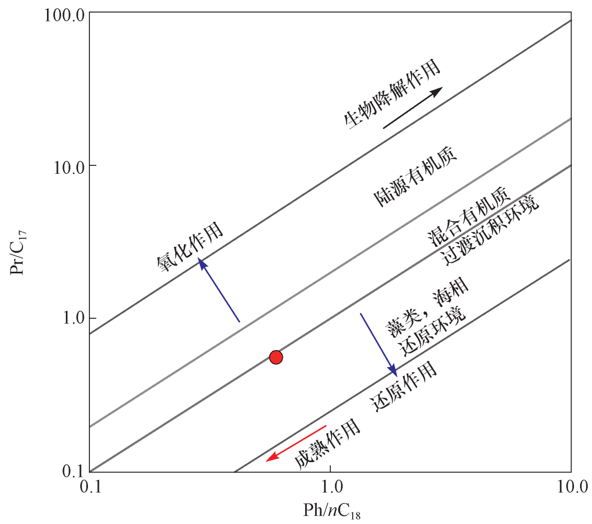

图 5　渭河盆地原油 Pr/nC_{17} 与 Ph/nC_{18} 关系（修编自文献[6]）

Fig. 5　$Pr/n\ C_{17}$ vs. Ph/nC_{18} rat ios of crude oil samples from the Weihe Basin(modified from reference[6])

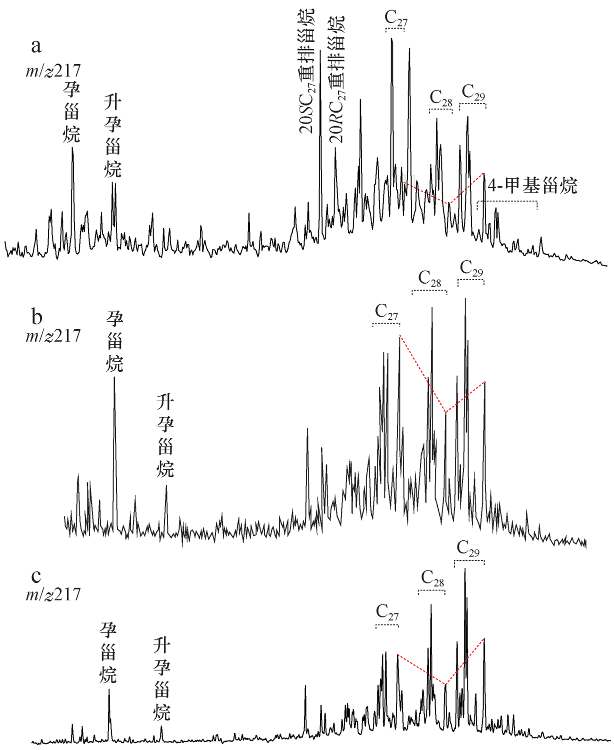

图 6　渭河盆地与鄂尔多斯盆地原油甾烷气相色谱-质谱

Fig. 6　Gas chromatographic-mass spectrometry of crude oil samples from the Weihe and Ordos Basins

a. 渭河盆地原油；b. 鄂尔多斯盆地天环坳陷南段侏罗系原油[4]；c. 鄂尔多斯盆地西峰地区三叠系延长组原油

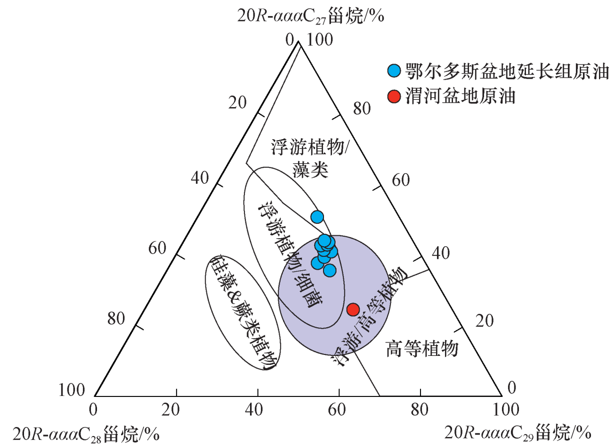

图 7　渭河盆地与鄂尔多斯盆地原油规则甾烷 C_{27}，C_{28} 和 C_{29} 组成三角图（修编自文献[12]）

Fig. 7　Ternary diagram showing C_{27}，C_{28} and C_{29} contents of regular sterane in crude oil samples from the Weihe and Ordos Basins(modified from reference[12])

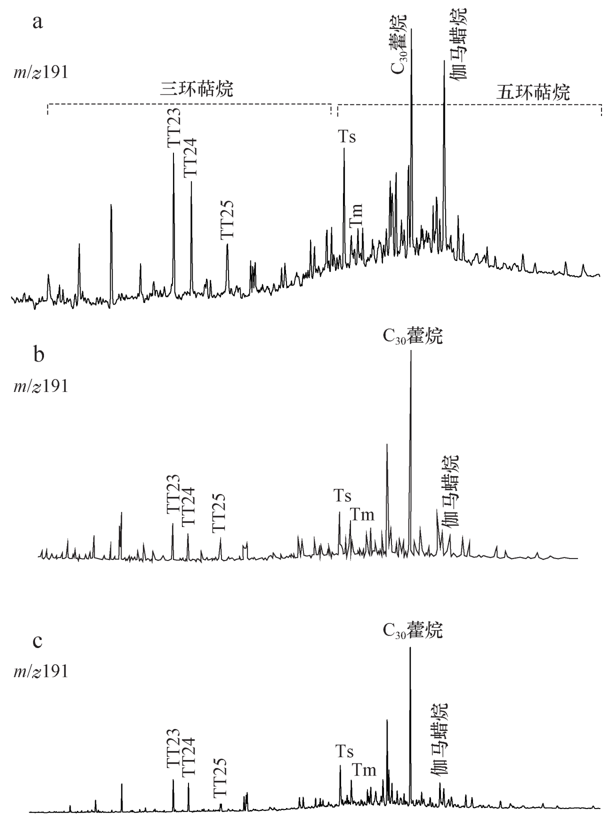

图 8　渭河盆地与鄂尔多斯盆地原油萜烷气相色谱-质谱

Fig. 8　Gas chromatography-mass spectrometer of terpane of crude oil sample from the Weihe and Ordos Basins

a. 渭河盆地原油；b. 鄂尔多斯盆地天环坳陷南段侏罗系原油[4]；c. 鄂尔多斯盆地西峰地区三叠系延长组原油

度参数[13]。原油的 $\beta\beta/(\beta\beta+\alpha\alpha)$，$\alpha\alpha 20S/(20S+20R)C_{29}$，甾烷值均为 0.56，显示原油母质处于成熟生油的演化阶段。这与 *OEP* 和 *CPI* 反映的原油母质成熟度一致。

原油的萜烷（m/z 191）主要由三环萜烷和五环萜烷组成（图 8）。三环萜烷相对含量与成熟度和生物降解作用等有关[13-15]。渭河盆地油样 C_{23} 萜烷明显较

高,指示咸化湖和海相环境;三环与五环三萜烷比值较高,为0.97;正构烷烃分布完整,未显示生物降解迹象(图4)。所以,其较高的三环萜烷主要与较高的成熟度有关。Ts[18α(H)-22,29,30-三降藿烷]比Tm([7α(H)-22,29,30-三降藿烷]抵抗成熟的能力强,但也与烃源岩沉积环境有关[16-17]。原油的Ts/Tm值为2.17,这与其较高的母质成熟度是吻合的[18-19]。

原油和烃源岩中的三环萜烷和四环萜烷与有机质来源有关,可用来判断母质形成的沉积环境[5,19](图9)。三环和四环萜烷参数关系显示了原油分布接近盐湖与海相沉积环境。此外,伽马蜡烷含量与沉积环境的水体盐度有关,盐度越高,伽马蜡烷含量越高[16,20-21]。渭河盆地原油伽马蜡烷含量明显很高,伽马蜡烷与C_{30}藿烷比值高达0.91,远高于鄂尔多斯盆地延长组原油(图10)。这表明了渭河盆地原油母质形成于较高盐度沉积环境的水体中。

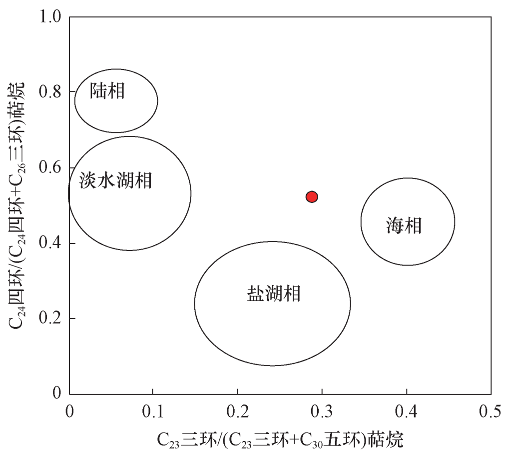

图9 渭河盆地原油C_{23}三环/(C_{23}三环+C_{30}五环)萜烷-C_{24}四环/(C_{24}四环+C_{26}三环)萜烷关系(修编自文献[19])

Fig. 9 C_{23} tricyclic/(C_{23} tricyclic + C_{30} pentacyclic) ratios vs. C_{24} tetracyclic/(C_{24} tetracyclic + C_{26} tricyclic) terpane ratios of crude oil sample from the Weihe Basin (modified from reference[19])

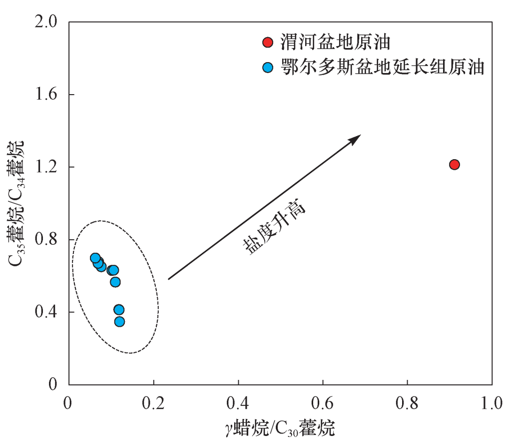

图10 渭河盆地与鄂尔多斯盆地原油γ蜡烷/C_{30}藿烷-C_{35}藿烷/C_{34}藿烷关系

Fig. 10 Gammacerane/C_{30} hopanevs. C_{35} hopane/C_{34} hopane of crude oil sample from the Weihe and Ordos Basins

原油五环三萜烷中较高的C_{35}藿烷普遍与海相碳酸盐岩或蒸发环境有关[22-23],也与盐湖沉积有关[24-25]。该油样的C_{35}藿烷相对含量较高,藿烷指数[HHI=C_{35}/(C_{31}—C_{35})]藿烷为0.15,C_{35}藿烷/C_{34}藿烷值高达1.21,也表明了原油母质形成于较高盐度的沉积水体中。

4 原油饱和烃单体烃碳同位素组成特征

原油饱和烃的单体烃碳同位素组成受控于母质来源与沉积环境,与沉积水体盐度有关,半咸水环境比淡水环境下沉积的有机质及其产物更富集重碳同位素$\delta^{13}C$[26-27]。分析发现,渭河盆地原油中低碳数(C_{14}—C_{22})的正构烷烃碳同位素值随碳数增加从-27.1‰降低到-30.3‰;当碳数高于C_{22}后,碳同位素值在-29.3‰和-30.4‰变化,其中异构烷烃比正构烷烃的碳同位素值要重一些;姥鲛烷(Pr)和植烷(Ph)的碳同位素值明显要重,分别为-26.1‰和-24.9‰(图11),明显比鄂尔多斯盆地延长组淡水湖湘原油$\delta^{13}C$值-31‰~-34‰重。总的显示出原油母质形成较高盐度的水体中[26-29]。

5 原油芳烃特征

芳烃化合物复杂而稳定,可用来进行油源对比、进行有机质成熟度评价、确定沉积环境以及生油的初次运移[30-32]。三芴系列化合物可用于指示源岩或者原油形成时的沉积环境,渭河盆地原油芳烃"三芴"系列组成中芴、氧芴、硫芴相对含量分别为1.32%,64.51%和34.17%,其形成环境与鄂尔多斯盆地各层位原油有明显差异(图12),并通过Pr/Ph与硫芴/氧芴关系图可看出渭河盆地原油形成于弱氧化-弱还原环境(图13),这与之前所判断的形成于弱还原环境并不矛盾。

6 特殊原油发现的油气地质意义

综合上述地化分析可见,该油样的烃源岩母质主

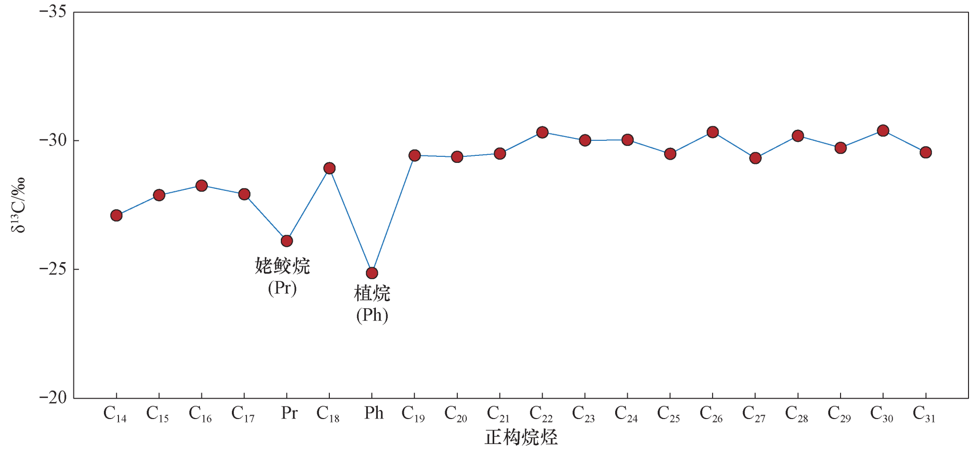

图 11　渭河盆地原油饱和烃单体烃碳同位素分布

Fig. 11　Distribution of carbon isotope values of saturated monomer hydrocarbons of crude oil sample from the Weihe Basin

要形成于弱还原的、盐度较高的湖相沉积环境，藻类等水生生物为烃源岩母质的主要有机质来源，有少部分高等植物的贡献，母质处于成熟的生油阶段。这种特征的原油与鄂尔多斯盆地发现的延长组、侏罗系、二叠系等层位中的原油都有较大的差别，显示了其明显的地球化学与成因的特殊性。

渭河盆地历史上曾经是古生代大华北盆地和中生代大鄂尔多斯盆地的一部分[33]，其前新生代地层的沉积、演化必然和鄂尔多斯盆地（华北地块）密切相关，其前新生界烃源岩与鄂尔多斯盆地相关层位烃源岩母质类型应有较多的相关性。渭河盆地新生代以来的断陷沉降和鄂尔多斯盆地走上不同的演化途径，渭河盆地特殊原油与鄂尔多斯盆地发现的中生界及古生界原油都不同[24-36]，最大可能来自新生界烃源岩。

渭河盆地新生代沉积最厚可达 6 000 ~ 7 000 m，发育古近系户县群（红河组、白鹿原组、甘河组），新近系高陵群（冷水沟组、龚家沟组）、蓝田组 - 灞河组、张家坡组，第四系三门组，自下而上可划分为下粗上细的 4 大沉积旋回，即古近系上始新统—渐新统（红河组 - 白鹿原组 - 甘河组）旋回、新近系中新统（高陵群）旋回、上新统（灞河组 - 蓝田组 - 张家坡组）旋回和第四系（三门组—秦川组）旋回[37]。目前钻井仅揭示高陵群以上地层，缺少钻穿古近系钻孔。目前地表露头及钻孔显示渭河盆地新生界初新近系张家坡组局部发育未成熟烃源岩外，主要为红层沉积[38]，显然本次发现的特殊原油与张家坡组无关，由于钻井深度有限（高陵群未穿），其烃源岩尚未钻达，即盆地内古近系和露头区应该存在相变，发育有还原环境的较高盐度湖相沉积。目前露头区古近系认为是低盐度河湖相沉积[39]，与盆地内古近系沉积相带的空间演化关系需进一步研究。

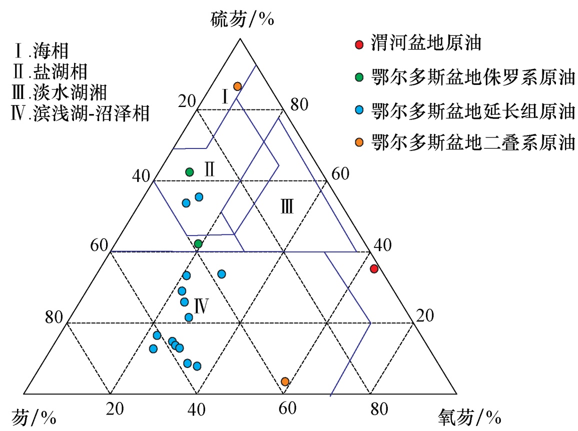

图 12　渭河盆地与鄂尔多斯盆地原油芴、硫芴、氧芴三角图（修编自文献[30][32]）

Fig. 12　Ternary diagram of fluorene, sulfur fluorene and dibenzofuran of crude oil sample from the Weihe and Ordos Basins (modified from reference[30], [32])

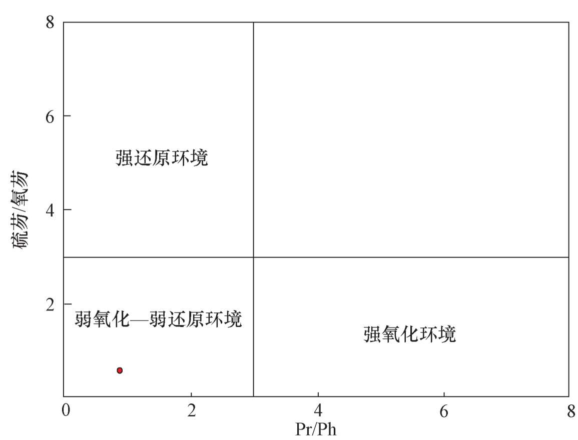

图 13　渭河盆地原油 Pr/Ph 与硫芴/氧芴关系（修编自文献[30]）

Fig. 13　Cross diagram between the Pr/Ph and sulfur fluorene/dibenzofuran of crude oil sample from the Weihe Basin (modified from reference[30])

渭河盆地油气勘探的主要矛盾是缺乏烃源岩,已有研究认为渭河盆地可能存在上古生界烃源岩[33,40-41],本次发现揭示渭河盆地还应具有尚未发现的生烃源岩,进一步表明渭河盆地具有油气资源前景,在已发现的“一热两气”(地热、氦气、生物气)基础上,还有石油蕴藏的含油气多能源盆地。

7 结论与认识

渭河盆地新发现的原油属于正常的含蜡、低硫、轻胶质原油,烃源岩母质主要形成于还原的、盐度较高的湖相沉积环境,藻类等水生生物为烃源岩母质的主要有机质来源,有少部分高等植物的贡献,是一种与鄂尔多斯盆地已发现的延长组、侏罗系、二叠系等层位原油都有较大差别的原油,烃源岩以处于成熟生油演化阶段,与渭河盆地已知的新近系张家坡组低熟-未熟烃源岩无关。由于钻井深度有限,未发现烃源岩,但根据地质背景分析渭河盆地应存在尚未发现的生烃源岩,烃源岩层位及其分布有待进一步研究。新发现原油进一步增加了渭河盆地将成为中国又一个含油气盆地的依据,具有重要的油气地质意义,同时也可为鄂尔多斯周缘盆地群新层系油气调查提供借鉴。

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