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南堡2号构造带中浅层油源对比及原油运聚模式

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摘要:南堡凹陷2号构造带中浅层原油为成熟轻质原油,具有低密度、低粘度、低凝固点、含蜡、低硫和胶质的特点,基本未遭受生物降解。基于烃源岩和原油地球化学特征精细研究,将南堡2号构造带烃源岩分为I类和II类,发育层位分别以沙三段—沙二段和东三段为主,I类烃源岩优于II类;原油分为A类、B类和C类,A类原油中伽马蜡烷含量低,B类原油伽马蜡烷含量相对较高,这3类原油中的C₂₇,C₂₈和C₂₉规则甾烷分别呈典型的“√”型、“L”型和“V”型,生烃母质具有低等水生生物和高等植物双重输入特征,主要形成于弱氧化—弱还原的淡水湖泊环境。A类、B类原油分别与I类、II类烃源岩具有亲缘关系,C类原油为混源油。在此基础上,明确不同类型原油的来源,依据源储关系建立中浅层原油运聚模式。油源断裂是深层油气向上运移的通道,断裂封闭性控制断裂两侧储层的含油气性和原油类型,深层超压为深层油气向中浅层圈闭运移提供动力,烃源岩与断裂的空间关系影响中浅层原油类型及分布。

关键词:烃源岩 原油类型 油源对比 运聚模式 油源断裂

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Oil-source correlation and model of migration and accumulation of shallow-middle crude oil in No.2 Structural Belt, Nanpu Sag

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Abstract: Middle-shallow crude oil is mature and light with the characteristics of low-density, low-viscosity, low-chill point, waxy, low-sulfur and colloid in No.2 Structural Belt of the Nanpu Sag, which is not biodegraded basically. Based on the geochemical characteristics of source rocks and crude oil, the source rocks are divided into Type I and Type II, which are respectively distributed in E_{s3+2} and Ed. The Type I source rock is better than the Type II. The crude oil can be divided into Type A, Type B and Type C. Type A oil has lower gammacerane content, while Type B oil has higher gammacerane content. The regular sterane C₂₇, C₂₈, C₂₉ of the three types of crude oil are characterized by the typical features of “√”, “L” and “V”. The kerogens are from both lower hydrobiont and higher plants, which are formed in lacustrine environment characterized by weakly oxic to weakly reducing fresh water. Type A and Type B crude oil are respectively related to Type I and Type II source rocks, and Type C of crude oil is from both Type I and Type II source rocks. On this basis, the source of different crude oil could be determined, and according to the relation of the source and the reservoir, the model of oil and gas migration and accumulation in middle-shallow reservoirs was established. The faults act as paths for upward migration of deep oil and gas. The crude oil types and petroliferous property in both side of the faults are controlled by fault sealing. Abnormal high pressure in deep stratigraphy provides driving force for the migration of deep oil and gas. The relationship between

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source rocks and faults influences the distribution and type of the middle-shallow crude oil.

Key words: source rock; types of crude oil; oil-source correlation; model of migration and accumulation; oil-source fault

南堡凹陷油气资源丰富,且多层系含油^[1-2]。南堡2号构造带是南堡凹陷有利的油气富集区,中浅层主要发育复杂断块油藏,前人对南堡2号构造带中浅层原油类型和油源均做过研究^[2-5],但对主力烃源岩发育在沙一段和东三段^[3-4],还是沙三段—沙二段^[6]仍存在争议。为此,笔者基于前人研究成果,通过南堡2号构造带中浅层油源对比研究,结合烃源岩和原油地化特征,将原油成因类型进行划分,确定中浅层油气来源,并依据源储关系建立研究区中浅层原油运聚模式,以期明确油气运移路径,进而落实新的勘探目标^[7]。

1 区域地质概况

南堡凹陷是渤海湾盆地黄骅拗陷北部的一个二级构造单元^[1-2],总面积约为1 932 km²,其中滩海面积约为1 000 km²,陆上面积约为932 km²[2],南堡凹陷由拾场次凹、柳南次凹、林雀次凹、曹妃甸次凹、高柳构造带、北堡—老爷庙构造带和南堡1—5号构造带组成(图1)^[1-2],自下而上依次发育奥陶系、古近系沙河街组(包括沙三段、沙二段和沙一段)、东营组(包括东三段、东二段和东一段)和馆陶组、新近系明化镇组(包括明化镇组下段和上段)及第四系平原组,且各层系均有油气发现^[2]。南堡凹陷中浅层指东一段、馆陶组和明化镇组^[8],生储盖组合为下生上储型,沙河街组和东三段是研究区重要的烃源岩发育层系^[4,8-9]。东营组主要发育三角洲—扇三角洲相中—低孔、中—低渗透储层,明化镇组和馆陶组主要发育河流相中—高孔、中—高渗透储层。馆陶组底部泥岩和玄武岩、明化镇组下段泥岩为良好盖层,东二段为厚度大且分布稳定的区域性盖层^[8]。南堡凹陷分别在沙三段—沙二段、东营组和明化镇组沉积时期发育“三期六型”断裂系统^[10-11],中浅层油气的主要充注期约为明化镇组沉

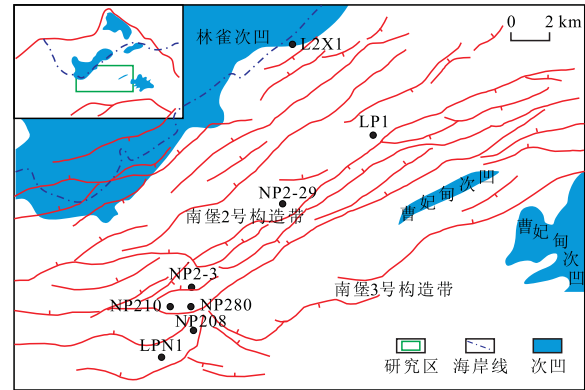


图1 南堡2号构造带区域构造位置

Fig.1 Structural position of No.2 Structural Belt, Nanpu Sag

积末期,断裂对沉积体系和油气富集具有明显地控制作用^[12-16],油气分布受明化镇组沉积末期活动的油源断裂的控制^[17-18]。

2 原油特征

2.1 原油物性与族组分特征

密度、粘度和含硫量等重要的原油物理参数均与其母质类型、成烃环境和次生变化等密切相关^[19]。南堡2号构造带中浅层原油为典型的淡水陆相轻质原油,具有低密度、低粘度、低凝固点、含蜡、低硫和胶质等特点,其中馆陶组原油密度和粘度等均小于东一段(表1),反映中浅层封闭条件好,原油运移过程中受层析效应控制,重烃组分被吸附,轻质组分增加,使得由东一段到馆陶组原油密度和粘度等均变小^[20-21]。

原油样品族组分分析结果显示,原油中饱和烃为优势组分,含量为59.09%~79.69%,平均为63.51%;其次为非烃+沥青质,含量为1.45%~29.07%,平均为16.18%;芳烃含量较低,为8.72%~22.34%,平均为14.10%。表明其生烃母质具有低等水生生物和陆源高等植物双重输入特征^[17]。

表1 南堡2号构造带中浅层原油物性统计

Table1 Statistics of physical properties of shallow-middle crude oil in No.2 Structural Belt, Nanpu Sag

层位	20℃密度/(g·cm ⁻³)		50℃粘度/(mPa·s)		凝固点/℃		含蜡量/%		含硫量/%		(胶质+沥青质含量)/%							
	样品数/个	区间	平均值	样品数/个	区间	平均值	样品数/个	区间	平均值	样品数/个	区间	平均值						
馆陶组	7	0.817 6~0.843 3	0.828 3	7	2.04~3.28	2.91	7	-6~24	10.66	7	4.13~10.4	7.55	7	0.02~0.16	0.08	6	6.98~18.8	10.75
东一段	24	0.805 0~0.888 8	0.842 9	24	1.68~25.76	6.53	24	2~26	6.53	24	3.52~18.75	10.60	24	0.04~0.54	0.11	22	4.35~26.44	11.78

2.2 原油地球化学特征

2.2.1 原油饱和烃特征

中浅层原油/油砂饱和烃总离子流谱图(TIC)基线平直,表明南堡2号构造带中浅层原油基本未遭受生物降解、氧化和水洗等后生作用,正构烷烃分布具有单峰型和双峰型2种形态,其中双峰型指示具有低等水生生物和高等植物的双重输入特征^[4]。油砂样品低分子烃类略低于原油样品,这可能与轻质组分挥发有关。原油碳优势指数(CPI)为1.02~1.19,平均为1.15,主要为正常的成熟原油; $(\sum nC_{21}/\sum nC_{22}^+)$ 与 $(nC_{21}+nC_{22})/(nC_{28}+nC_{29})$ 值分别为0.40~1.81(平均为1.06)和0.57~3.13(平均为2.01),表明原油轻质组分含量高,以轻质油为主。

原油中Pr/nC₁₇和Ph/nC₁₈值与生烃母质类型和成熟度有关^[22-24]。南堡2号构造带中浅层原油Pr/nC₁₇和Ph/nC₁₈值大多在混合相区域,反映生烃母质类型主要为混合型(图2)。此外,Pr/Ph值常被用来确定沉积环境的氧化—还原性^[25],分析结果显示,Pr/Ph值为0.83~1.45,平均为1.19;Pr/nC₁₇值为0.30~1.96,平均为0.58;Ph/nC₁₈值为0.25~2.11,平均为0.54,表明其生烃母质形成于弱氧化—弱还原环境。

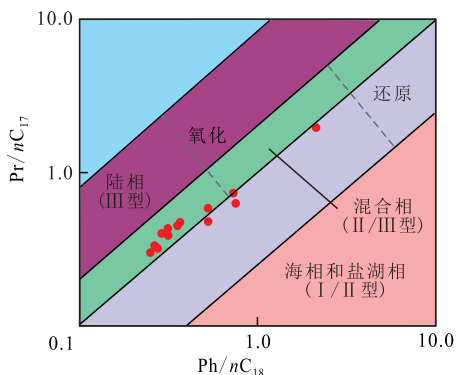


图2 南堡2号构造带中浅层原油Pr/nC₁₇与Ph/nC₁₈关系

Fig.2 Relationship between Pr/nC₁₇ and Ph/nC₁₈ of shallow-middle crude oil in No.2 Structural Belt, Nanpu Sag

2.2.2 原油甾萜烷特征

原油的甾萜烷特征可以反映其母质输入、沉积环境和成熟度等特征^[25]。南堡2号构造带原油中C₂₇, C₂₈和C₂₉规则甾萜烷具有“√”型、“L型”和“V型”3种典型形态,反映其生烃母质具有低等水生生物和陆源高等植物双重输入的特点(图3)。C₃₀-4-甲基甾萜烷含量和伽马蜡烷含量总体偏低,生烃母质形成于淡水湖泊环境。甾萜烷异构化参数是常用的成熟度参数,其中C₂₉甾萜烷的异构化值最为常用^[25-26]。研究区Ts/Tm, CPI, C₂₉ββ/(αα+ββ)和C₂₉ααα20S/(20S+20R)值分别为0.78~1.50(平均为1.01),

1.02~1.19(平均为1.15),0.35~0.51(平均为0.41)和0.37~0.47(平均为0.42),以成熟原油为主(图4)。

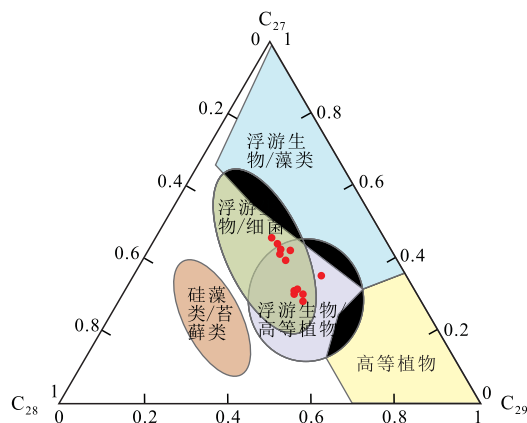


图3 南堡2号构造带中浅层原油C₂₇, C₂₈和C₂₉规则甾萜烷相对含量三角图

Fig.3 Triangle chart of relative content of regular sterane C₂₇-C₂₈-C₂₉ of shallow-middle crude oil in No.2 Structural Belt, Nanpu Sag

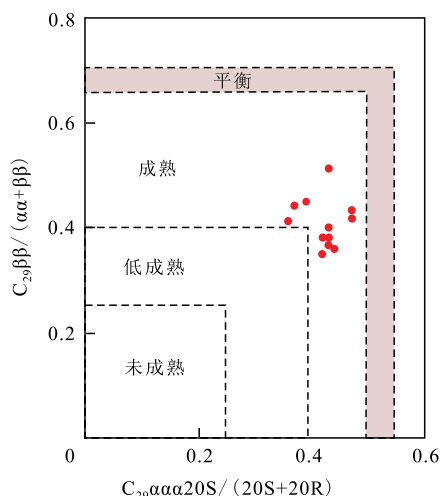


图4 南堡2号构造带中浅层原油甾萜烷异构化指标分布

Fig.4 Distribution map of alkane isomerization index from shallow-middle crude oil in No.2 Structural Belt, Nanpu Sag

3 原油分类与油源对比

3.1 油源特征

南堡2号构造带主要发育沙河街组湖泊相暗色泥岩和东三段三角洲—湖泊相泥岩。随着深度的增加,各层段泥岩总有机碳含量(TOC)呈线性增加,沙河街组烃源岩有机质丰度最高(图5a);东三段烃源岩有机质类型最好(图5b)。结合C₂₇, C₂₈和C₂₉规则甾萜烷和伽马蜡烷含量等特征,将烃源岩分为I类和II类2种类型, I类烃源岩主要为沙河街组湖相泥岩,主要发育层位为沙三段—沙二段,部分发育在沙一段,TOC达0.67%~2.70%,平均为1.67%,生

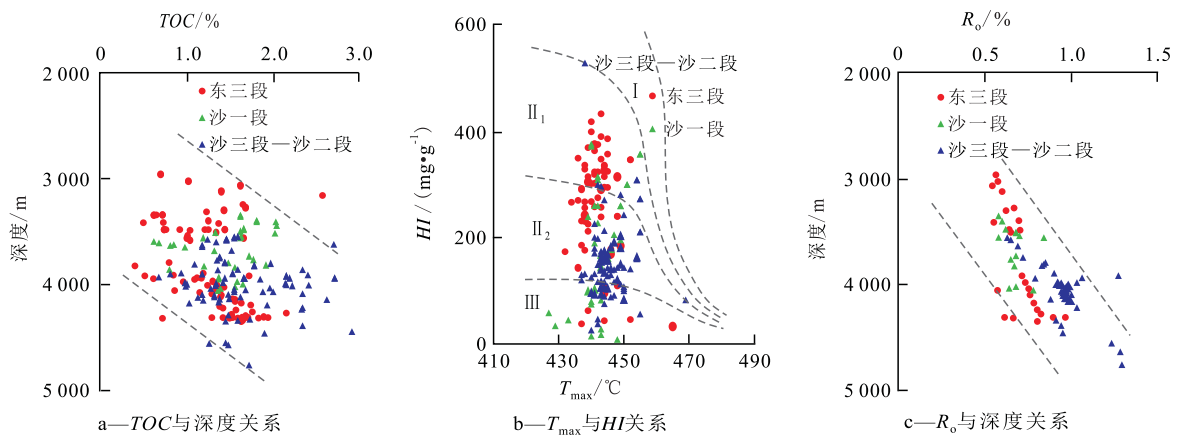


图5 南堡2号构造带烃源岩评价

Fig.5 Evaluation of source rock from No.2 Structural Belt, Nanpu sag

烃潜量(S_1+S_2)为1.34~11.79 mg/g,平均为3.35 mg/g,为好烃源岩,母质类型主要为Ⅲ型干酪根, R_o 值为0.63%~1.29%,平均为0.95%,处于成熟阶段。 C_{27} , C_{28} 和 C_{29} 规则甾烷呈“√”型,反映生烃母质以陆源高等植物输入为主,伽马蜡烷含量很低。Ⅱ类烃源岩主要位于东三段,有机碳含量较高,达0.49%~2.56%,平均为1.27%, S_1+S_2 值为0.70~9.54 mg/g,平均为3.78 mg/g,为较好—好烃源岩,母质主要为Ⅱ₁—Ⅱ₂型干酪根, R_o 值为0.54%~1.19%,平均为0.73%,处于低熟—成熟阶段(图5c)。 C_{27} , C_{28} 和 C_{29} 规则甾烷呈“L”型,说明生烃母质以低等水生生物输入为主,伽马蜡烷含量略高于Ⅰ类。由烃源岩有机质丰度、类型和成熟度参数综合分析表明,Ⅰ类烃源岩优于Ⅱ类烃源岩(图5)。

3.2 原油分类

研究区不同类型原油 C_{27} , C_{28} 和 C_{29} 规则甾烷特征明显,结合TIC, T_s/T_m 和伽马蜡烷等地化参数将南堡2号构造带中浅层原油划分为A类、B类和C类。A类原油中 C_{27} , C_{28} 和 C_{29} 规则甾烷呈“√”型特征, C_{30} -4-甲基甾烷含量较低, C_{30} 藿烷含量高,伽马蜡烷含量低,生烃母质以陆源高等植物输入为主。B类原油 C_{27} , C_{28} 和 C_{29} 规则甾烷呈“L”型特征, C_{30} -4-甲基甾烷含量低, C_{30} 藿烷含量高,伽马蜡烷含量略高于A类,表明其生烃母质以低等水生生物输入为主。C类原油正构烷烃呈双峰型, C_{27} , C_{28} 和 C_{29} 规则甾烷呈“V”型特征, C_{30} -4-甲基甾烷含量低, C_{30} 藿烷含量高,伽马蜡烷含量低,表明其生烃母质具有低等水生生物和陆源高等植物双重输入特征(图6)。

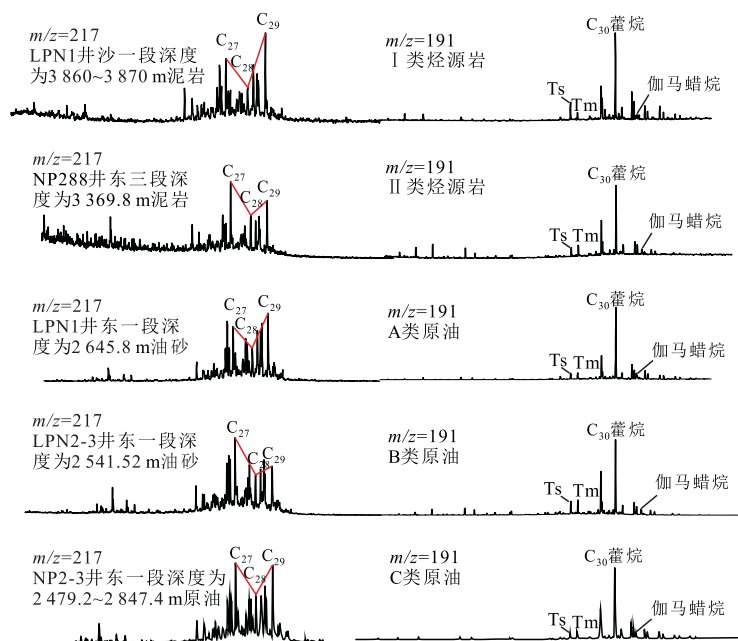


图6 南堡2号构造带典型烃源岩和原油色谱质谱图

Fig.6 GC-MS spectrograms of typical source rock and crude oil from No.2 Structural Belt, Nanpu Sag

3.3 油源对比

基于研究区烃源岩与原油研究,表明南堡2号构造带原油和烃源岩具有较好对应关系。A类原油与I类烃源岩具有良好的亲缘关系,伽马蜡烷含量低, C_{27} , C_{28} 和 C_{29} 规则甾烷呈“√”型,主要来自深层沙河街组烃源岩,以陆源高等植物输入为主。B类原油与II类烃源岩具有良好的亲缘关系,伽马蜡烷含量高于A类, C_{27} , C_{28} 和 C_{29} 规则甾烷呈“L”型特征,主要源自东三段烃源岩,以低等水生生物输入为主。C类原油为A类和B类原油的混源油,原油特征介于A类和B类之间,伽马蜡烷含量低, C_{27} , C_{28} 和 C_{29} 规则甾烷呈“V”型特征,具有低等水生生物和陆源高等植物双重输入(图6)。

4 原油运聚模式

南堡2号构造带中浅层油藏的成藏条件复杂,

受多种因素控制。中浅层为下生上储型组合模式,沙河街组和东三段的暗色泥岩均可作为烃源岩,油气来源充足。储层物性随深度增加呈阶梯状减小,中浅层储层物性普遍优于深层(图7a, 7b)。东二段是南堡2号构造带稳定的区域性盖层,从东二段(深度约为3 000 m)开始,泥岩声波时差(AC)偏离正常压实趋势线,前人研究成果表明,南堡凹陷东二段及以下地层普遍发育超压,这为深层油气向中浅层运移提供动力(图7c)^[27],馆陶组底部的玄武岩或玄武质泥岩是良好的盖层,有利于油气保存,超压与盖层的存在均为油气成藏提供了保障。

油源对比结果表明,LPN1井东一段原油属于A类,来自沙一段烃源岩^[10],沙一段生成的油气通过 F_1 断裂向上进行垂向运移,在东一段和馆陶组聚集成藏。NP208井馆陶组原油为B类,LPN1井东一段深度为2 460.0~2 499.0 m试油,获产油量为260.91 m^3/d ,产气量为15 600~17 500 m^3/d ; NP208井东一

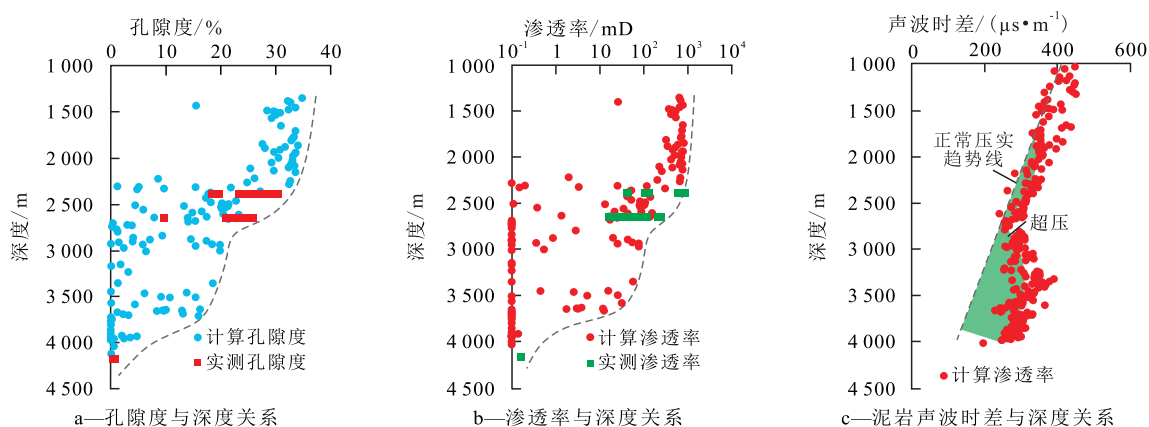


图7 南堡2号构造带LPN1井物性及泥岩声波时差与深度关系

Fig.7 Relationship among porosity, permeability, mudstone sonic log interval and depth of the Well LPN1 in No.2 Structural Belt, Nanpu Sag

段深度为2 447.2~2 548.0 m试油,获产油量为62.44 m^3/d ,产气量为8 910 m^3/d ; LPN1井东一段产量明显高于NP208井。图8显示LPN1井东一段实测地层压力明显高于邻井(NP280井无实测压力数据,用NP210井代替)。由于过断层压差可以间接反映断层的侧向封闭性,即断层的侧向封闭性越好,其过断层压差越大^[28]。 F_1 断裂在东一段封闭,使得 F_1 断裂两侧具有不同的压力系统、含油气性和原油类型,且遮挡断层的侧向封堵性影响油气分布。

此外, NP2-3井东一段存在B类原油和C类混源油,由图9可以看出, I类和II类烃源岩生成的原油均通过 F_2 断裂向上运移,在中浅层聚集成藏,烃源岩与断裂的空间关系也影响中浅层原油类型及分布。

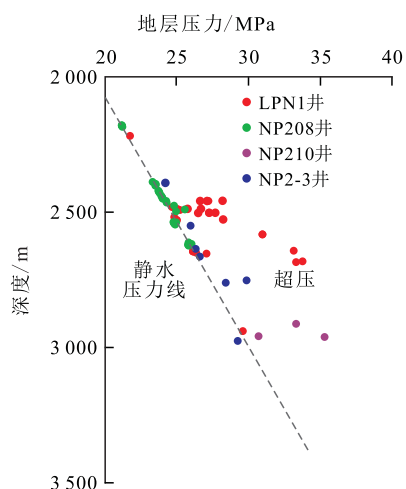


图8 南堡2号构造带地层压力与深度关系

Fig.8 Relationship between formation pressure and depth in No.2 Structural Belt, Nanpu Sag

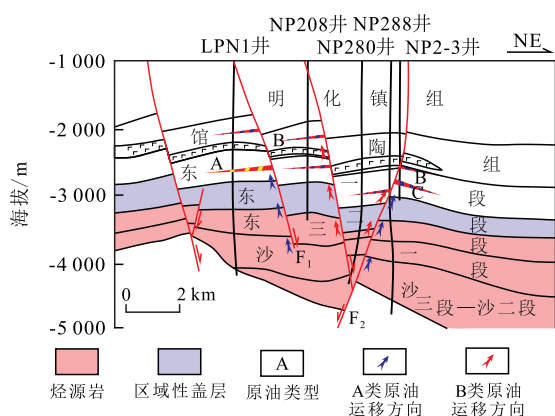


图9 南堡2号构造带中浅层原油成藏模式

Fig.9 Model of shallow-middle crude oil migration and accumulation in No.2 Structural Belt, Nanpu Sag

5 结论

南堡2号构造带中浅层发育低密度、低粘度、低凝固点、含蜡、低硫和胶质的成熟轻质原油，基本未遭受生物降解。原油族组分的饱和烃含量高，生烃母质具有低等水生生物和陆源高等植物双重输入特征，主要形成于弱氧化—弱还原环境。

研究区烃源岩分为Ⅰ类和Ⅱ类，原油分为A类、B类和C类。Ⅰ类和Ⅱ类烃源岩分别以沙三段—沙二段和东三段暗色泥岩为主，Ⅰ类烃源岩优于Ⅱ类。A类、B类原油分别与Ⅰ类、Ⅱ类烃源岩具有亲缘关系，C类为混源油，A类原油伽马蜡烷含量很低，B类相对较高，原油中C₂₇、C₂₈和C₂₉规则甾烷分别呈典型的“√”型、“L”型和“V”型。油源断裂是深层油气向上运移的通道，断裂封闭性控制断裂两侧储层的含油气性及原油类型。深层普遍发育超压，超压为深层油气向中浅层运移提供动力，烃源岩与断裂的配置关系影响中浅层原油类型及分布。

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