

渤海湾盆地临南洼陷古近系沙河街组源-储组合类型与致密(低渗)砂岩油差异富集模式

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摘要:为了揭示渤海湾盆地临南洼陷古近系沙河街组致密(低渗)砂岩油的差异富集机理,在依据空间配置和岩性组合划分源-储组合类型的基础上,综合利用测井、录井、试油和岩心分析测试资料,对不同源-储组合类型含油性及其供烃条件、储集条件、输导条件和运聚动力进行了分析,建立了致密(低渗)砂岩油差异富集模式。结果显示:①研究区存在源-储共生型(夹层型、互层型)、源-储紧邻型(源上型、源间型和源下型)、源-储间隔型(源下型)3大类6亚类源-储组合,对应3种致密(低渗)砂岩油富集模式。②源-储共生型具有“强供烃-强动力-高效充注-储集控富”模式,供烃条件和运聚动力最优,油气通过孔缝高效充注,储层含油性最好;相较于互层型,砂体厚度制约了夹层型油气富集规模。③源-储紧邻型具有“较强供烃-差异动力-联合输导-多元控富”模式,供烃条件较好,运聚动力变化大,油气通过孔缝-断裂-砂体联合输导,优先充注物性和孔隙结构好的储层,储层含油性较好;亚类中,源间型供烃条件和运聚动力优于源上型和源下型,含油性最好。④源-储间隔型具有“弱供烃-弱动力-断砂输导-输储控富”模式,供烃和运聚动力较弱,断裂、砂体组成的有效输导通道和优质储层发育对于油气富集至关重要,含油性整体较差。

关键词: 富集条件; 富集模式; 源-储组合; 致密(低渗)砂岩油; 古近系; 临南洼陷; 渤海湾盆地

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Source rock-reservoir assemblage types and differential oil enrichment model in tight (low-permeability) sandstone reservoirs in the Paleocene Shahejie Formation in the Linnan Sub-sag, Bohai Bay Basin

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Abstract: This study aims to reveal the differential oil enrichment mechanisms of tight (low-permeability) sandstone reservoirs in the Paleogene Shahejie Formation in the Linnan Sub-sag, Bohai Bay Basin. Initially, we categorize the source rock-reservoir assemblages in the Linnan Sub-sag based on their spatial distribution and lithologic combination. The analysis on oil-bearing properties, hydrocarbon supply, reservoir storage spaces, conduit system, and migration and accumulation dynamics of various source rock-reservoir assemblages is carried out using an integration of data of logging, well tests, production tests and core analysis and tests. Accordingly, the differential oil enrichment model is established for tight (low-permeability) sandstone reservoirs. The results indicate that the source rock-reservoir assemblages in the study area can be categorized into three types, which can be further divided into six subtypes: the source-reservoir coexistence type, including interbedded and intercalated sub-types; the source-reservoir adjoining type, comprising three distinct subtypes with reservoirs located above, between, or below source rocks; and the source-

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reservoir separation type, including a subtype with reservoirs located below source rocks. These types correspond to three oil enrichment model of the tight (low-permeability) sandstone reservoirs. The source-reservoir coexistence type exhibits an oil enrichment model featuring “a strong hydrocarbon supply, strong migration and accumulation dynamics, efficient charging, and reservoir-controlled oil enrichment.” Specifically, this type boasts the optimal hydrocarbon supply conditions, the strongest migration and accumulation dynamics, and efficient hydrocarbon charging via pores and fractures, all of which contribute to the most favorable oil-bearing properties. Compared to that of the intercalated subtype, the hydrocarbon enrichment scale of the interbedded subtype is restricted by sand-body thicknesses. The source-reservoir adjoining type manifests an oil enrichment model characterized by a comparatively strong hydrocarbon supply, differential migration and accumulation dynamics, combined conduit systems, and multiple factor-controlled oil enrichment. In detail, this type features a comparatively favorable hydrocarbon supply, significant changes in the migration and accumulation dynamics, and combined conduit systems consisting of pores, fractures, faults, and sand bodies, with hydrocarbon preferentially charging reservoirs with favorable physical properties and pore structures. This type of source rock-reservoir assemblage exhibits comparatively favorable oil-bearing properties. Among others, its subtype with reservoirs located between source rocks outperforms the other two subtypes in terms of both hydrocarbon supply and migration and accumulation dynamics, thus demonstrating the optimum oil-bearing properties. The source-reservoir separation type displays a pattern characterized by a weak hydrocarbon supply, weak migration and accumulation dynamics, conduit systems including faults and sand bodies, and oil enrichment under the control of conduits and reservoirs. Due to the weak hydrocarbon supply and migration and accumulation dynamics, effective transport pathways composed of faults and sand bodies, along with the presence of high-quality reservoirs, are crucial to hydrocarbon enrichment. This type of source rock-reservoir assemblage generally exhibits inferior oil-bearing properties.

Key words: enrichment condition, enrichment model, source rock-reservoir assemblage, oil in tight (low-permeability) sandstone reservoirs, Linnan Sub-sag, Bohai Bay Basin

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全球致密油气资源丰富,勘探开发潜力巨大^[1-2]。国际上对致密油气的研究目前主要集中在致密储层特征和油气运移、充注与赋存机理方面^[3-6]。中国致密油气勘探开发虽然起步较晚,但是近几年在准噶尔盆地二叠系、鄂尔多斯盆地三叠系延长组、四川盆地侏罗系、松辽盆地白垩系和渤海湾盆地古近系等地区取得了重大突破^[7],显示出广阔的勘探开发前景。

致密油具有源-储共生或近源富集的特征^[8-9],源-储组合是致密油成藏与富集的核心要素和基本单元^[10-12]。前人依据源-储空间配置、源-储岩性组合和源-储接触关系等,建立了多种致密油源-储组合类型划分方案,并分析了优势源-储组合类型^[13-16];少数学者还探索了不同源-储组合下的成藏动力、运移方式和储集性能^[17-19],为致密油气勘探提供了有益指导。然而源-储组合类型差异下的致密砂岩油富集机理研究尚不深入,制约了致密油气成藏理论的进一步发展和勘探开发方案的制定。

临南洼陷是渤海湾盆地重要的含油气洼陷,沙河街组沙三中亚段—沙四上亚段致密(低渗)砂岩油资源丰富,多套烃源岩与储层相互叠置、连片分布,构成了相对复杂的源-储配置关系,储层含油性差异显著,加大了勘探开发难度。本次研究利用胜利油田勘探开发研究院提供的测井、录井、试油和物性资料,基于中国石油大学(华东)深层油气全国重点实验室开展的烃源岩地化、储层物性、薄片观察、压汞分析测试资料,通过划分不同的源-储组合类型,探讨了致密(低渗)砂岩油差异富集条件,以期揭示该地区致密(低渗)砂岩油差异富集机制,为研究区及类似地区的油气勘探开发提供理论指导。

1 地质概况

临南洼陷位于渤海湾盆地东南部,洼陷北部以临商断裂为界毗邻中央隆起带,南部以夏口断裂为界与

南部斜坡带相连(图1a),发育不对称的地堑式结构。研究区新生界自下而上依次发育古近系孔店组、沙河街组和东营组,新近系馆陶组、明化镇组和第四系平原组(图1b),由于沙三下亚段厚度较大,将沙三下亚段细分为上部(1—3层组)和下部(4—6层组)。

临南洼陷沙三中亚段—沙四上亚段存在多套烃源

岩,其中沙三下亚段上部1层组和3层组发育深湖—半深湖相泥页岩,在研究区分布稳定,厚度范围分别为30~150 m和20~120 m;总有机碳含量(TOC)介于0.1%~19.2%,平均2.9%;有机质类型以I—II₁型为主,镜质体反射率(R_o)分布在0.66%~1.18%,主体进入生油高峰,供油能力强,油源对比已证实其为研究区主力

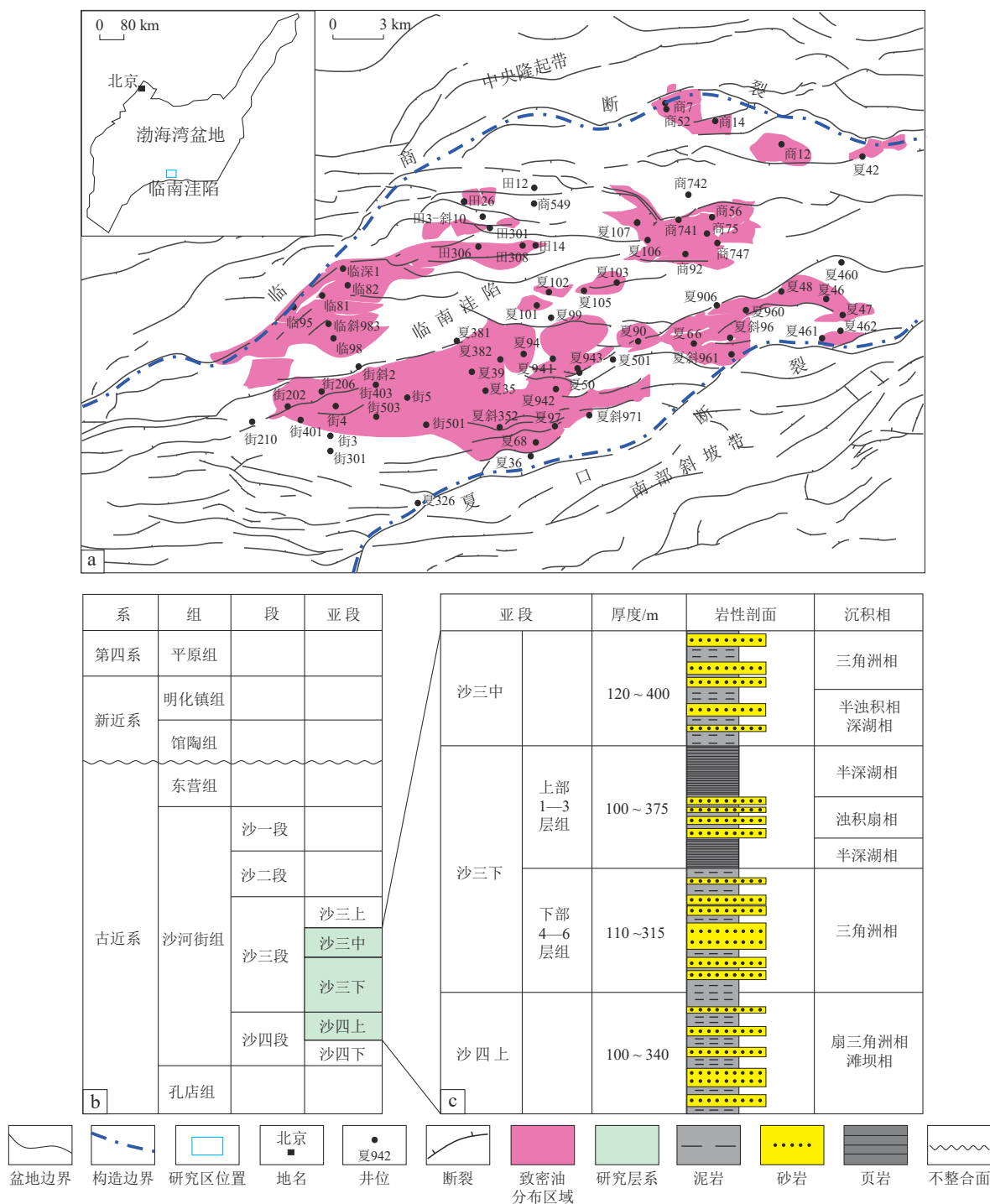


图1 临南洼陷构造特征及致密(低渗)砂岩油分布(a)与地层发育特征(b)

Fig. 1 Structural characteristics and oil distribution in tight (low-permeability) sandstone reservoirs (a) and stratigraphic column (b) of the Linnan Sub-sag

烃源岩^[20]。其余层系泥岩非均质性强,生油能力极不均衡,可在局部地区形成有效烃源岩。

沙三中亚段—沙四上亚段沉积的源内和近源的浊积砂体、三角洲前缘砂体是致密(低渗)油勘探的主要对象,储层渗透率介于 $(0.009 \sim 922.700) \times 10^{-3} \mu\text{m}^2$,其中小于 $1 \times 10^{-3} \mu\text{m}^2$ 的占64.3%,小于 $10 \times 10^{-3} \mu\text{m}^2$ 的占92.9%。在洼陷中心致密(低渗)油呈现大面积连片分布,以岩性油藏为主;在洼陷边缘主要沿断裂带或邻近断裂分布,以构造-岩性油藏为主。

2 源-储组合类型与含油性差异

2.1 源-储组合类型及特征

临南洼陷除沙三下亚段上部,其余层系内的泥岩多数不具备生油能力,致密砂岩油主要表现为源外富集,因此难以简单依据源-储岩性组合进行划分;而与烃源岩直接接触的砂体占比较少,非直接接触砂体占多数,若依据源-储接触关系进行划分,势必会导致不同类型所涵盖的体量差异过大。因此,笔者以沙三中亚段、沙三下亚段上部、沙三下亚段下部、沙四上亚段

为基本单元,建立了基于源-储空间配置和岩性组合的源-储组合类型划分方案。

利用TOC测井评价技术识别烃源岩层段($TOC \geq 1.0\%$),利用测录井资料识别储层段,依据烃源岩层段与储层段的空间配置关系,将源-储组合类型划分为源-储共生型,源-储紧邻型和源-储间隔型。依据源-储岩性组合关系并参考砂-泥结构^[21],将源-储共生型进一步划分为夹层型(砂/地比 $<30\%$)和互层型(砂/地比 $\geq 30\%$)2个亚类,按照《页岩油地质评价方法》国家标准^[22]对页岩油的定义,去除夹层型中砂体厚度小于5m的组合;依据源-储相对位置,将源-储紧邻型和源-储间隔型进一步划分为源上型、源间型和源下型亚类。依据上述划分方案,将临南洼陷沙三中亚段—沙四上亚段划分为3大类6亚类源-储组合类型(图2)。

统计结果表明,研究区源-储组合类型中源-储紧邻型平面分布最为广泛,多与三角洲前缘亚相及浊积扇相砂体对应,占比69.1%,其中源上型占比19.1%,源间型占比16.7%,源下型占比33.3%;源-储共生型分布相对局限,通常与深水重力流浊积砂体对应,占比为18.0%,其中夹层型占比10.3%,互层型占比7.7%;由于钻井深度限制,源-储间隔型占比为

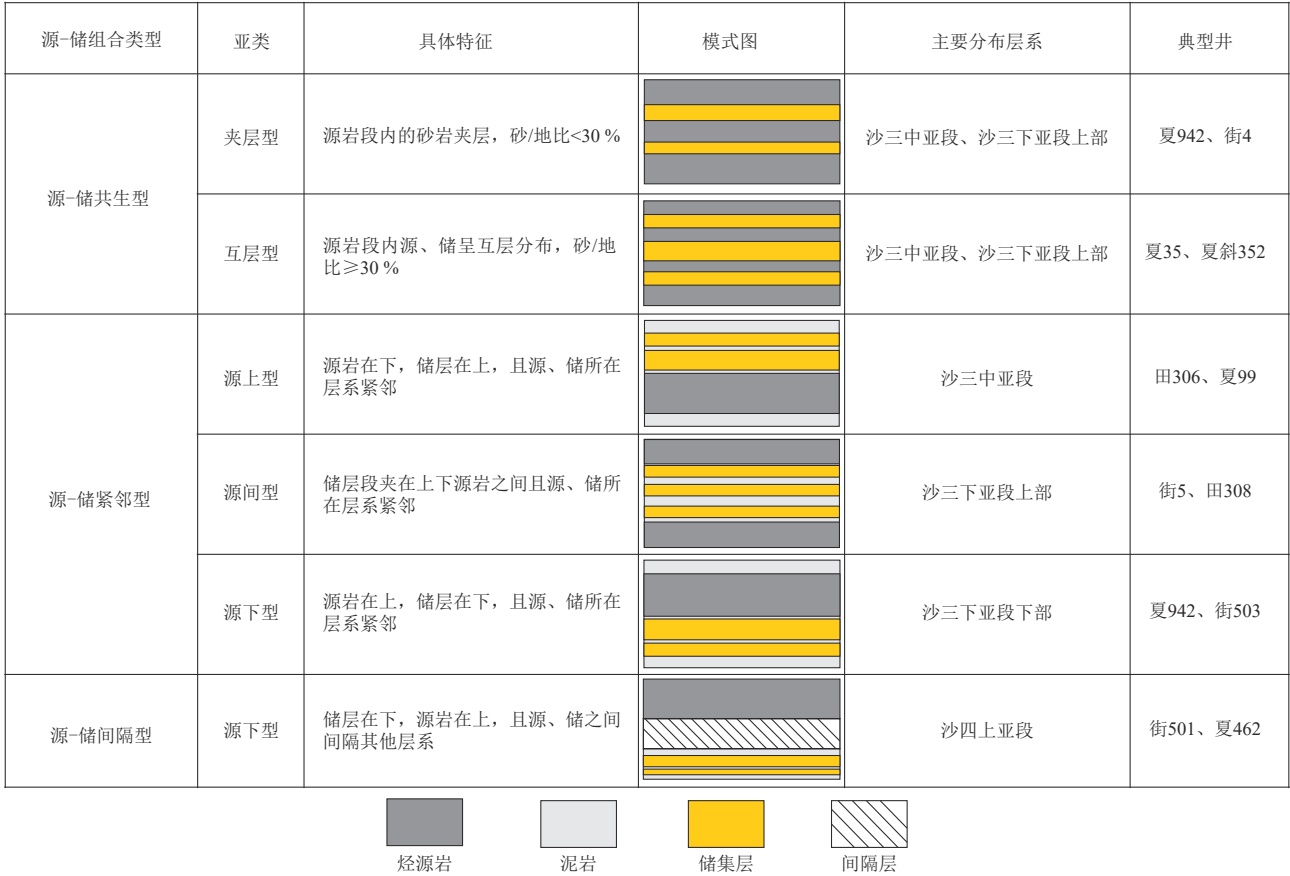


图2 临南洼陷源-储组合类型划分方案

Fig. 2 Classification scheme for source rock-reservoir assemblages in the Linnan Sub-sag

于28.0%~100.0%,平均55.9%,达到40%以上的井数占80.0%(图4a,b);在油气显示厚度与油气显示比例交会图中主要位于i区域,表明油气显示比例较高的同时,油气显示厚度偏小(图4c)。储层含油饱和度主要介于22.0%~83.0%,平均51.3%(图5a);平均日产油量11.40 t,日产水量仅0.74 t,产油量显著大于产水量(图5b)。在其2种亚类中,夹层型具有更高的油气显示比例和含油饱和度,但由于油气显示厚度偏薄,导致产油量低于互层型,综合比较认为互层型含油性更好。

源-储紧邻型含油性差于源-储共生型。油气显示比例介于9.0%~78.0%,平均43.5%,达到40%

以上的井数占62.8%(图4a,b);在油气显示厚度与显示比例交会图中分布较为分散,表明不同井之间差异较大(图4c)。储层含油饱和度主要介于17.5%~75.0%,平均41.6%(图5a)。平均日产油量6.40 t,日产水量2.40 t,产油量大于产水量(图5b)。在其3个亚类中,源间型油气显示比例、含油饱和度及产油量均为最高,具有最好的含油性,源上型和源下型含油性次之。

源-储间隔型含油性最差。油气显示比例介于2.5%~25.0%,平均11.6%,达到40%以上的井数仅占总数的10.0%(图4a,b);在油气显示厚度与显示比例交会图中主要位于iii区域,表明两者均偏小(图4c)。储

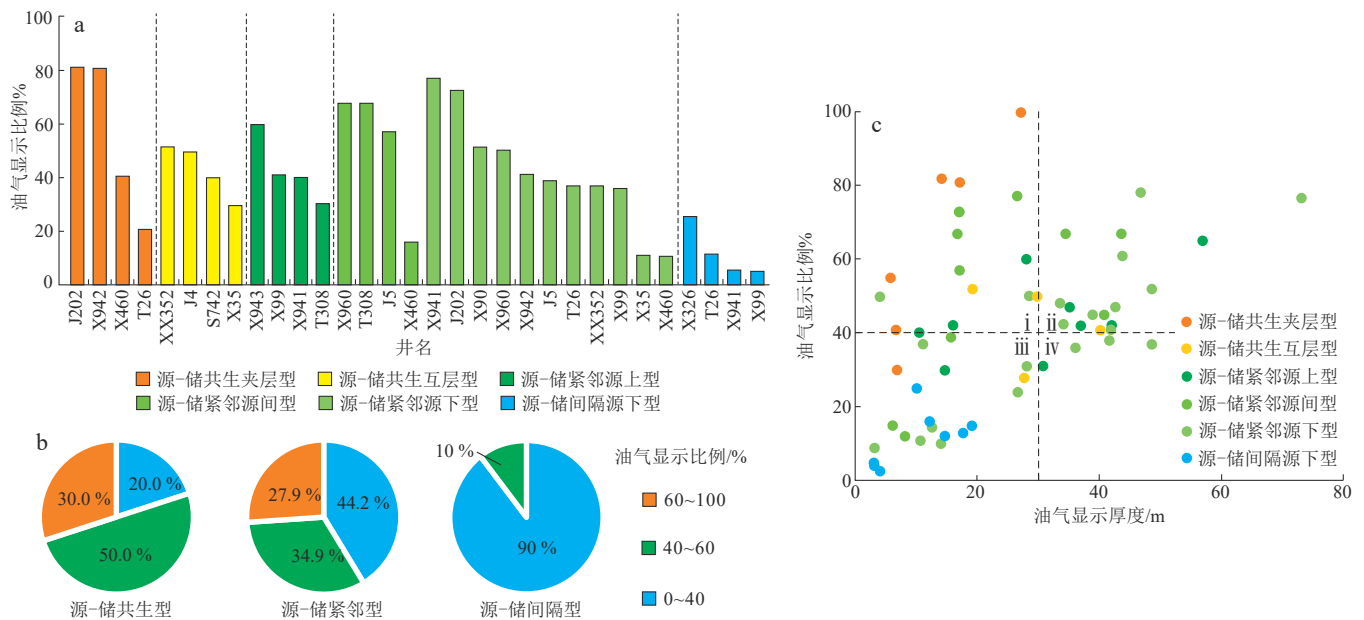


图4 临南洼陷不同源-储组合油气显示比例特征

Fig. 4 Hydrocarbon show proportions of various source rock-reservoir assemblages in the Linnan Sub-sag

a. 油气显示比例分布柱状图; b. 油气显示比例井数占比饼状图; c. 油气显示比例与油气显示厚度交会图

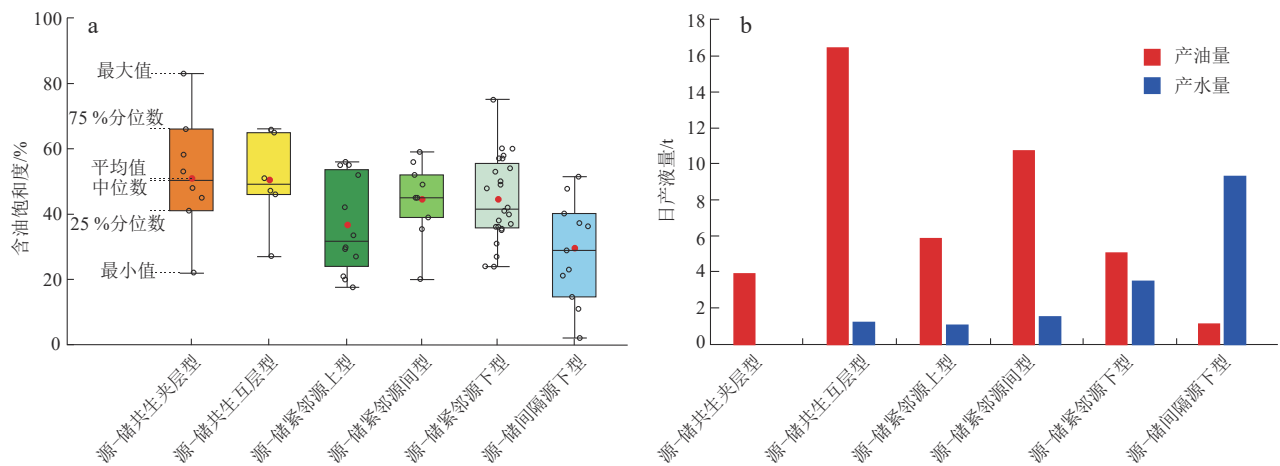


图5 临南洼陷不同源-储组合含油饱和度(a)和平均日产液量分布(b)

Fig. 5 Distributions of oil saturation (a) and average daily liquid production (b) of the various source rock-reservoir assemblages in the Linnan Sub-sag

层含油饱和度主要介于2.0%~51.0%,平均28.5%(图5a);平均日产油量1.10 t,日产水量9.40 t,产油量明显小于产水量(图5b)。

3 致密(低渗)油差异富集条件

3.1 供烃条件

供烃条件是致密(低渗)砂岩油富集的物质基础,具有重要的控制作用。综合考虑烃源岩特征及致密(低渗)油勘探实际,将研究区烃源岩划分为两类: $TOC > 2.0\%$, $R_o > 0.7\%$ 划定为优质烃源岩; TOC 介于 $1.0\% \sim 2.0\%$, R_o 介于 $0.5\% \sim 0.7\%$ 划定为普通烃源岩。

不同源-储组合烃源岩厚度和品质差异会影响供烃效率和强度,进而影响储层含油性。①源-储共生型烃源岩平均厚度180.6 m,优质烃源岩供烃占比70.0%(图6),储层与烃源岩直接接触,供烃条件和含油性最好;在其2个亚类中,夹层型优质烃源岩供烃占比更大,供烃条件优于互层型。②源-储紧邻型烃源岩平均厚度100.9 m,优质烃源岩供烃占比70.0%(图6),储层位于烃源岩层外,源-储接触面积显著减小,供烃条件整体弱于源-储共生型,含油性次之;在其3个亚类中,源间型可同时接受上下两套烃源岩供烃,供烃条件好于源上型和源下型。③源-储间隔型烃源岩厚度和优质烃源岩占比分别为66.9 m和42.8%(图6),储层与烃源岩层分离,整体供烃条件和含油性较差。

此外,随着烃源岩厚度增大,源-储共生和源-储紧邻型储层含油饱和度呈现逐渐增加的趋势;在厚度相近的情况下,优质烃源岩供烃比例更大的源-储组合往往具有更好的含油性(图6)。源-储间隔型则无以上规律,进一步统计发现其含油性随着源-储距离

增大而明显变差,分析原因可能是其原油富集受到供烃条件外的其他因素控制更为明显,较大的源-储距离会加大这些因素的控制效应。

3.2 运聚动力条件

运聚动力是致密油气成藏的重要控制因素之一^[24-25]。致密油成藏以非浮力驱动为主,一般来说,超压是主要运聚动力^[26-28]。临南洼陷烃源岩层内部砂体最大实测压力系数可达1.8,超压带发育深度与烃源岩主生油阶段深度重叠^[29-30],并且烃源岩开始生烃时间与储层中超压产生时间一致^[31]。此外,多种超压成因的测井响应特征判识方法的结果也指示超压主要由烃源岩生烃增压引起^[32]。

笔者通过郭小文等(2011)^[33]提出的定量模型计算了研究区沙三中亚段—沙四上亚段烃源岩理论生烃增压量,并将其作为致密(低渗)油运聚的主要动力。计算结果表明,研究区沙三中亚段—沙四上亚段优质烃源岩生烃增压量介于6.0~20.7 MPa,普通烃源岩则介于1.8~12.4 MPa,生烃能力更强的优质烃源岩明显产生了更大的超压。

源-储共生型油气运聚动力为源-储剩余压力差,而对于储层位于烃源岩层外的源-储紧邻型和源-储间隔型而言,难以用源-储剩余压力差表征运聚动力。因此,本次研究引入源-储剩余压力梯度的概念表征运聚动力($T, \text{MPa/km}$),其指烃源岩和储层之间单位距离内地层流体压力的变化幅度,是源-储剩余压力差和源-储距离的综合参数^[34]。计算公式如下:

$$T = (p_s - p_r) / L \quad (1)$$

式中:烃源岩剩余压力 p_s 取烃源岩生烃增压量,MPa;储层剩余压力 p_r 取储层段实测剩余压力,MPa;源-储距离 L 取源岩顶(底)面至储层段中点距离,km。

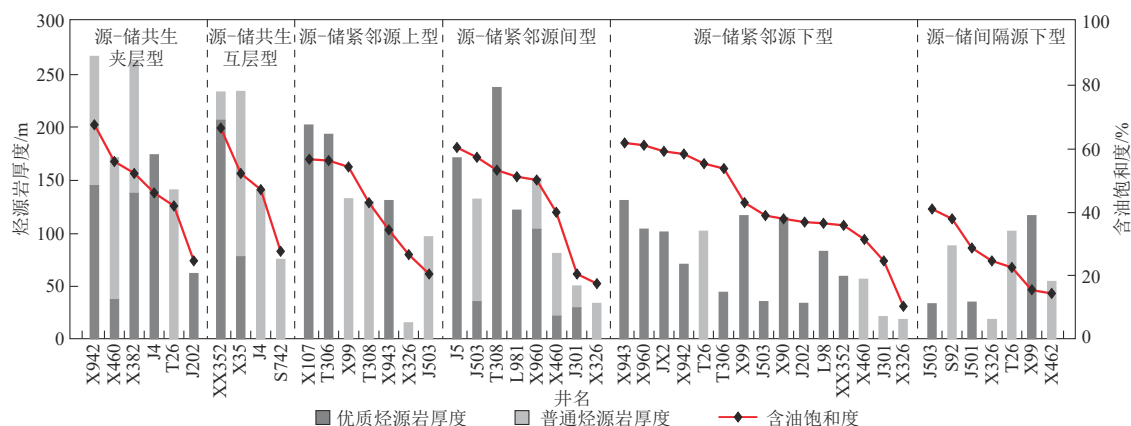


图6 临南洼陷不同烃源岩厚度、品质下各源-储组合类型含油饱和度统计

Fig. 6 Statistics of oil saturation of various source rock-reservoir assemblages with different thicknesses and quality of source rocks in the Linnan Sub-sag

计算结果表明,源-储共生型源-储剩余压力差介于3.0~16.9 MPa之间,平均8.0 MPa,运聚动力条件和含油性最好,夹层型亚类略大于互层型(图7a)。源-储紧邻型源-储剩余压力梯度变化较大,介于18~465 MPa/km,平均155 MPa/km,含油性次之;在其3个亚类中,源-储剩余压力梯度源间型>源下型>源上型(图7b)。源-储间隔型源-储剩余压力梯度普遍较小,介于5~60 MPa/km,平均30 MPa/km,运聚动力条件和含油性较差(图7b)。此外,随着源-储剩余压力差和剩余压力梯度增大,各源-储组合亚类中油气显示比例均具有增大趋势。由此表明,运聚动力条件是导致致密(低渗)油差异富集的重要因素之一。

3.3 油气输导条件

断层、裂缝和砂体是临南洼陷油气运移的主要输导要素^[35-37]。由于烃源岩和储层的空间位置不同,不同源-储组合的输导要素及组合情况存在明显差异。综合考虑以上因素,将研究区致密(低渗)砂岩油输导模式划分为:孔缝输导模式、孔缝-断裂-砂体联合输导模式和断裂-砂体输导模式。①源-储共生型对应孔缝输导模式。岩心观察表明烃源岩层内部主要发育层理缝和低角度缝(图8a),生成的油气通过裂缝排出后直接向相邻砂体充注,然后通过砂体内的孔隙和裂缝运移和聚集(图8g),油气运移距离最短、运移效率最高。②源-储紧邻型对应孔缝-断裂-砂体联合输导模式。对于与烃源岩直接接触的砂体,油气通过孔隙和裂缝从烃源岩层排出后,直接充注进入砂体运移和聚集;而未与烃源岩直接接触的砂体,断层和砂岩层段内发育的高角度、斜交构造裂缝和微裂缝提供了高效

的油气垂向运移通道(图8b—f),油气通过断层、裂缝、渗透性砂体输导运移后在储层内聚集。③源-储间隔型对应断裂-砂体输导模式。油气排出后必须通过断层、裂缝、渗透性砂体输导运移后才能成藏,油气运移距离较远,运移效率低。

可以看出,源外成藏的源-储紧邻型和源-储间隔型对输导条件要求较高,各输导要素的发育及组合情况控制了油气的运移范围与效率,例如夏46井和街501井区分别由于断裂和叠置砂体发育,均在相对远源的源-储间隔型储层内发现良好的油气显示。

3.4 储集条件

3.4.1 砂体厚度

储层发育规模是影响油气富集的关键条件之一^[25,38]。研究区不同源-储组合类型储层砂体厚度存在差异:源-储共生型砂体累计厚度在3大类源-储组合中最薄,平均43.8 m,其中互层型大于夹层型;源-储紧邻型累计厚度平均75.7 m,其中源下型>源上型>源间型;源-储间隔型砂体累计厚度平均72.9 m(图9a)。各源-储组合类型单砂体厚度主要分布在0~6 m,且源-储共生型在该区间内频率较源-储紧邻型和源-储间隔型更高(图9b)。结合不同源-储组合含油性差异可以看出,砂体厚度制约了源-储共生夹层型油气富集规模。

3.4.2 储层物性

物性是评价储层品质的宏观参数^[39-40],由于沉积类型、埋深、成岩作用的不同,临南洼陷致密(低渗)油

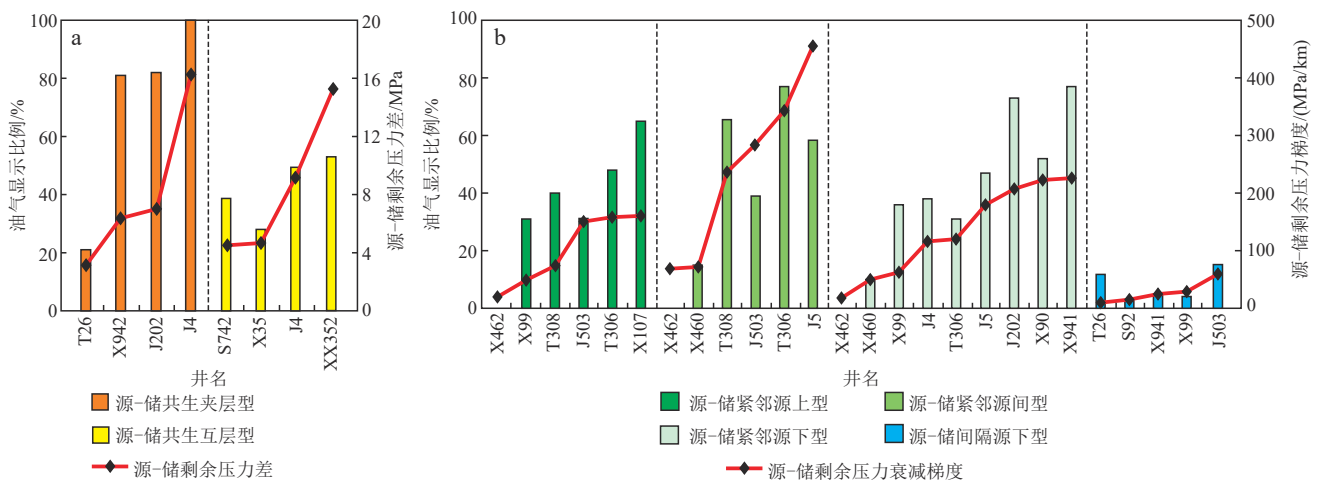


图7 临南洼陷致密(低渗)砂岩油运聚动力与油气显示比例关系

Fig. 7 Relationship between the migration and accumulation dynamics of oil in tight (low-permeability) sandstone reservoirs and the hydrocarbon show proportions in the Linnan Sub-sag

a. 源-储剩余压力差与油气显示比例关系; b. 源-储剩余压力梯度与油气显示比例关系

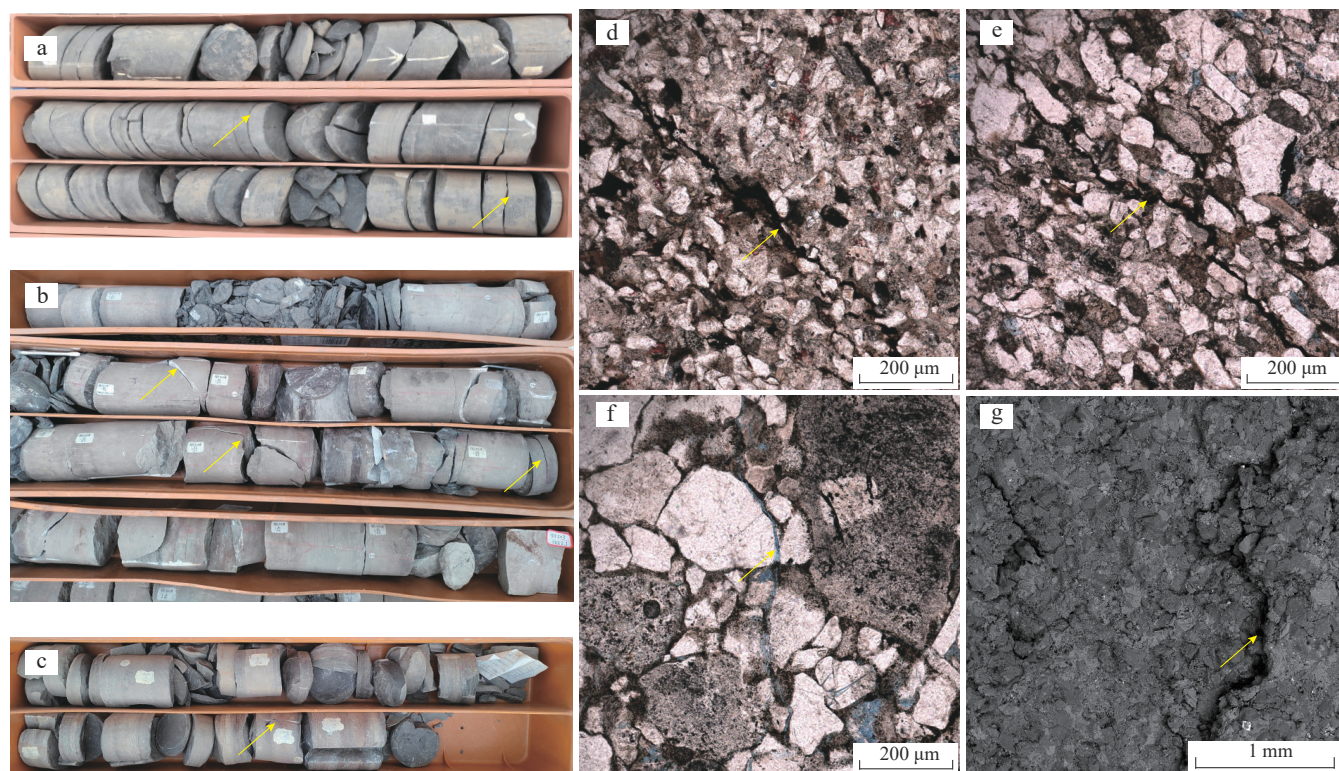


图8 临南洼陷沙三段—沙四段泥页岩与致密(低渗)砂岩储层裂缝特征

Fig. 8 Fractures in shales and tight (low-permeability) sandstone reservoirs in the 3rd and 4th members of the Shahejie Formation in the Linnan Sub-sag

a. 泥页岩层理缝及低角度缝,商741井,埋深3 350.0~3 353.0 m,岩心照片;b. 砂岩内高角度缝、斜交缝,源-储紧邻源间型,街503井,埋深3 848.1~3 852.1 m,岩心照片;c. 砂岩内高角度缝、斜交缝,源-储紧邻源下型,街4井,埋深3 956.5~3 958.0 m,岩心照片;d. 微裂缝内充填沥青,街5井,埋深3 933.6 m,源-储紧邻源间型,单偏光显微镜下照片;e. 微裂缝内充填沥青,街5井,埋深3 978.0 m,源-储紧邻源间型,单偏光显微镜下照片;f. 砂岩内微裂缝,夏942井,埋深3 800.8 m,源-储紧邻源下型,单偏光显微镜下照片;g. 砂岩内微裂缝,夏斜352井,埋深3 826.8 m,源-储共生互层型,扫描电镜照片

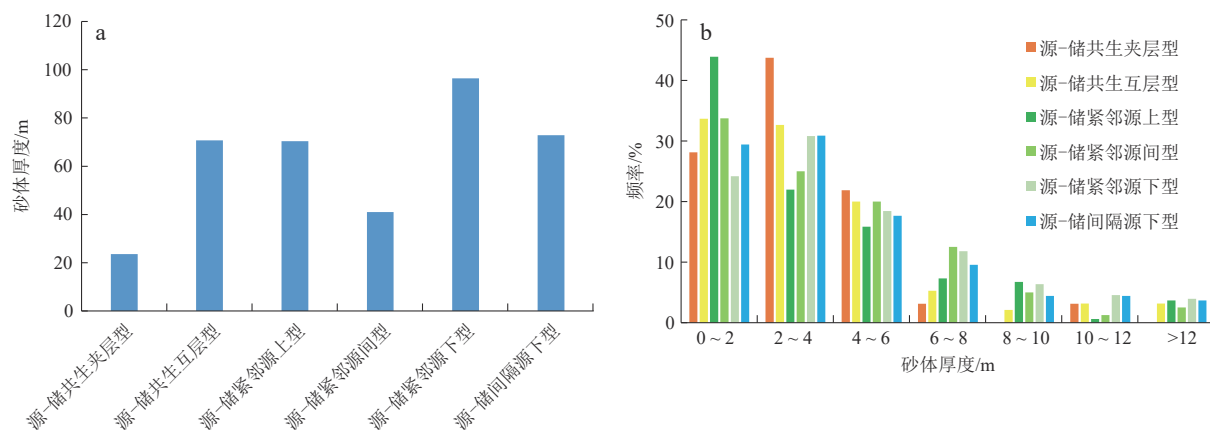


图9 临南洼陷不同源-储组合类型砂体厚度对比

Fig. 9 Histogram showing the sand-body thicknesses of different source rock-reservoir assemblages in the Linnan Sub-sag

a. 砂体累计厚度;b. 单砂体厚度

层段不同源-储组合类型的储层物性存在一定差异。整体来看,储层物性非均质性较强,其中源-储紧邻型储层物性最好,平均孔隙度12.5%,渗透率中值 $0.58 \times 10^{-3} \mu\text{m}^2$;源-储共生型次之,孔隙度平均9.6%,

渗透率中值 $0.50 \times 10^{-3} \mu\text{m}^2$;源-储间隔型较差,平均孔隙度8.5%,渗透率中值 $0.32 \times 10^{-3} \mu\text{m}^2$ 。为进一步研究物性对含油性的影响,笔者选取临南洼陷数据点较多的源-储紧邻型3个亚类统计物性与含油性的关系,可

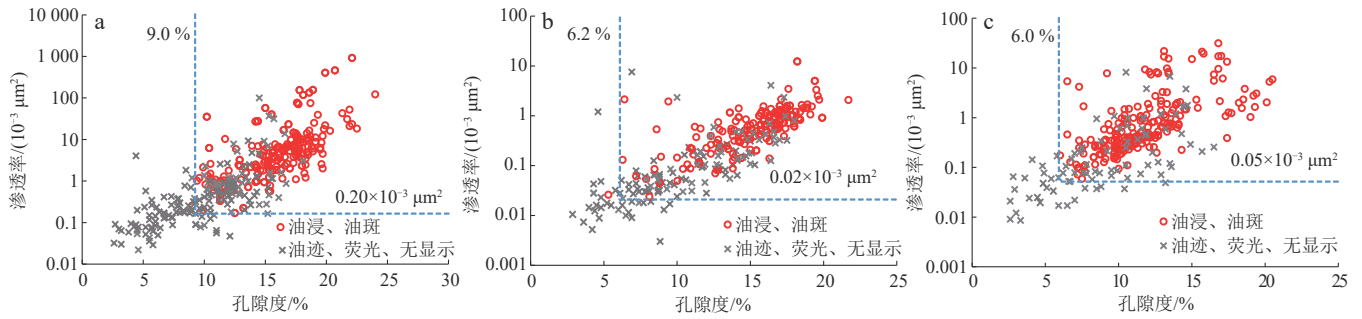


图10 临南洼陷源-储紧邻型源-储组合各亚类储层物性与含油性关系

Fig. 10 Relationships of the physical and oil-bearing properties of reservoirs in the three subtypes of the source-reservoir adjoining type in the Linnan Sub-sag

a. 源上型; b. 源间型; c. 源下型

以看出,虽然存在重合区间,但整体上物性更好的储层高含油级别(油斑、油浸)占比更大(图10),表明在其他成藏条件相对趋近的同源-储组合类型内部,储层物性对致密(低渗)砂岩油的分布具有重要控制作用,物性相对较好的部位(甜点)往往更容易富集油气。

3.4.3 储层孔隙结构

微观孔隙结构对储层储集性能和渗流能力等具有重要的影响,一直是致密砂岩油气成藏研究的重点之一^[41-43]。通过研究区致密(低渗)砂岩储层薄片及扫描

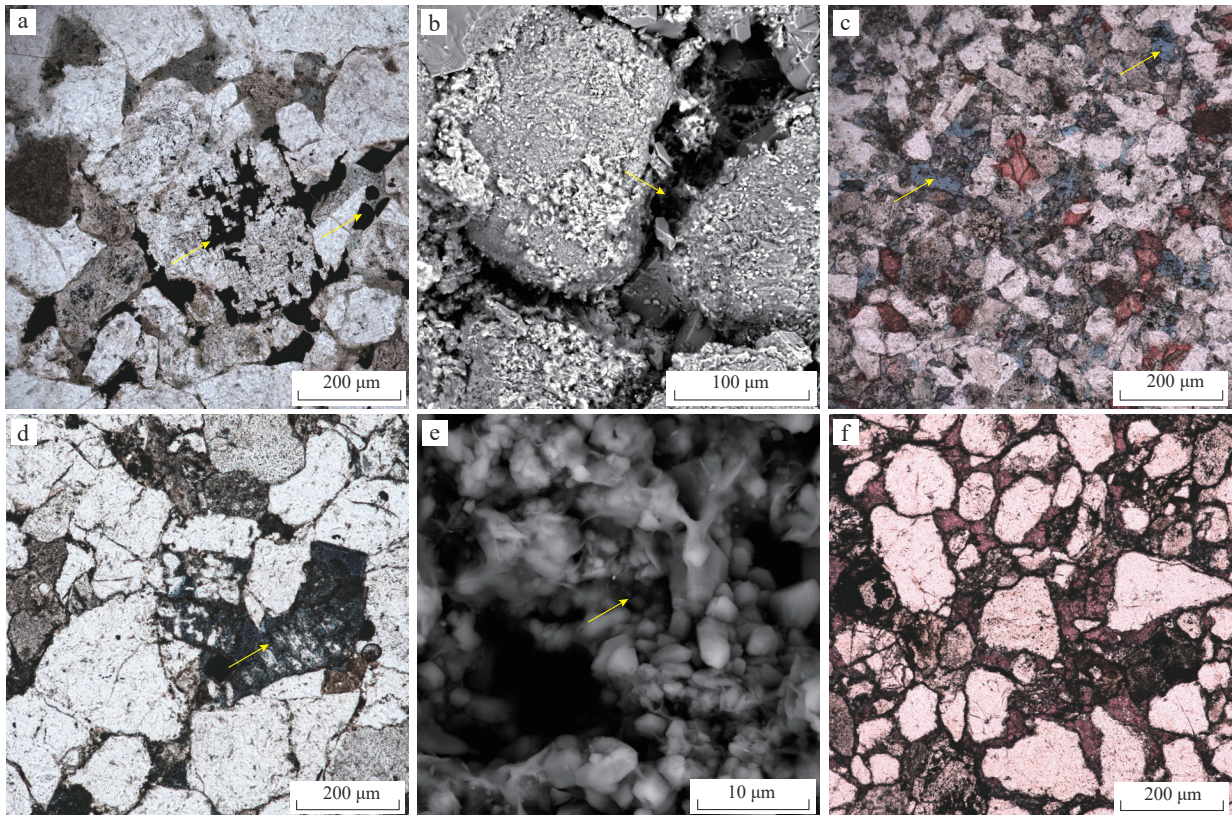


图11 临南洼陷致密(低渗)砂岩储层孔隙发育特征及含油性差异显微照片

Fig. 11 Micrographs showing pore developmental characteristics and oil-bearing property differences of tight (low-permeability) sandstone reservoirs in the Linnan Sub-sag

a. 残余粒间孔与次生溶蚀孔发育,内部赋存沥青,街503井,埋深4 047.3 m,源-储紧邻源下型,油浸,单偏光;b. 残余粒间孔发育,夏942井,埋深3 800.8 m,源-储紧邻源下型,油斑,扫描电镜;c. 镜下孔隙发育较差,夏99井,埋深4 253.2 m,源-储紧邻源下型,油迹,单偏光;d. 次生溶蚀孔隙发育,临82井,埋深3 869.6 m,源-储共生夹层型,油浸,单偏光;e. 石英晶间孔发育,夏斜352井,埋深3 826.8 m,源-储共生互层型,荧光,扫描电镜;f. 孔隙不发育,夏斜961井,埋深3 449.8 m,源-储间隔源下型,无显示,单偏光

电镜观察,源-储紧邻型储层孔隙最为发育,以残余粒间孔和次生溶蚀孔为主(图11a—c),发育少量微裂缝(图8d—f);源-储共生型和源-储间隔型孔隙发育相对较差,次生溶蚀孔和晶间孔增多(图11d—f)。而在同一源-储组合类型条件下,孔隙发育程度好的储层含

油性一般好于孔隙发育差或不发育的储层(图11)。

为了进一步分析孔喉大小、分布及连通性对含油性的影响,笔者通过压汞分析测试,对比临南洼陷各源-储组合不同含油性储层的孔隙结构差异(图12)。以源-储紧邻型为例(图12c,d),夏943井3 794.1 m深

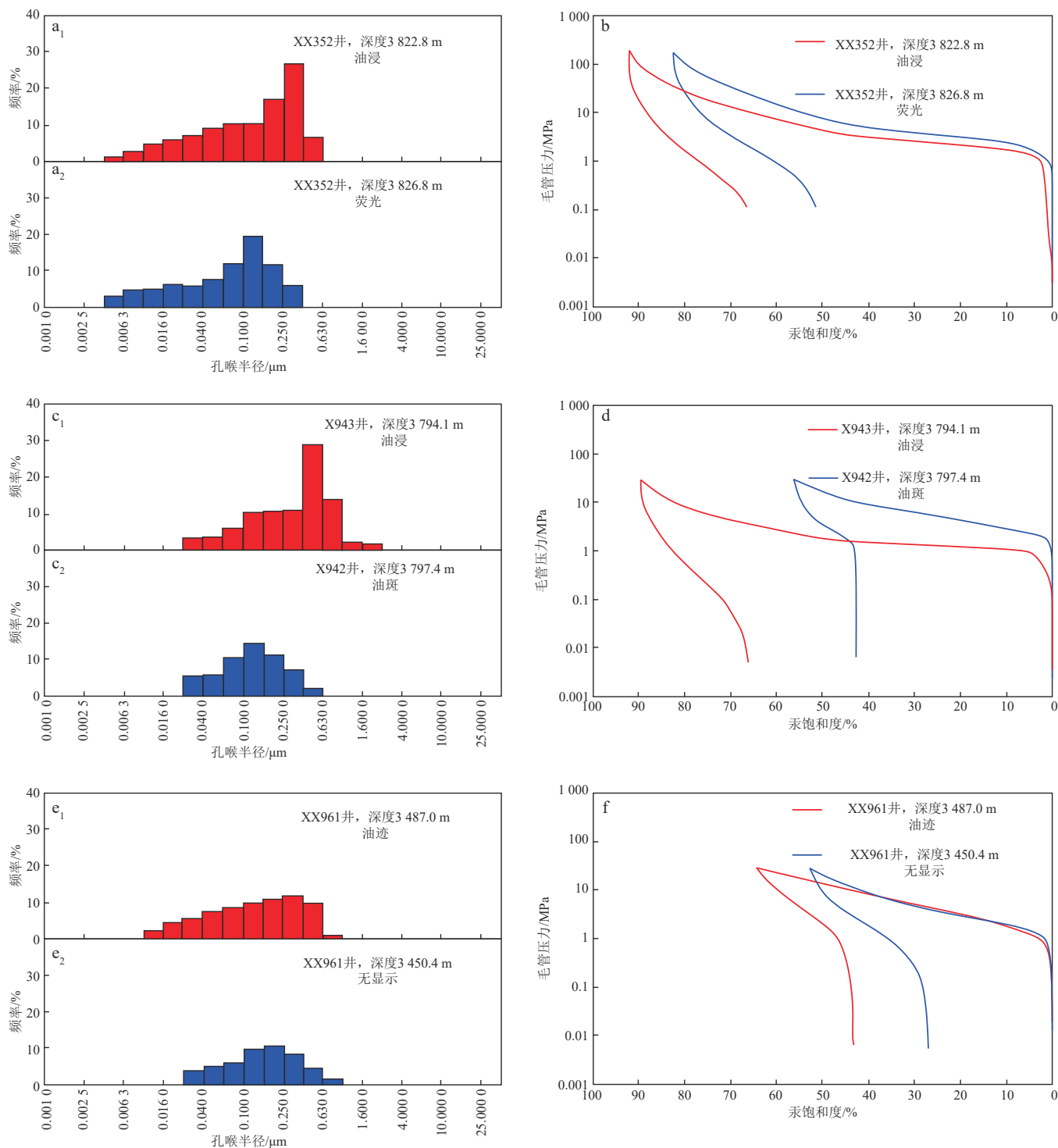


图12 临南洼陷致密(低渗)砂岩储层孔隙结构特征

Fig. 12 Pore structural characteristics of tight (low-permeability) sandstone reservoirs in the Linnan Sub-sag

a,b. 源-储共生型;c,d. 源-储紧邻型;e,f. 源-储间隔型

度样品孔喉半径峰值位于0.40~0.63 μm ,平均孔喉半径0.43 μm ,最大进汞饱和度88.4%,含油级别为油浸;而夏942井3797.4 m深度样品孔喉半径峰值位于0.10~0.16 μm ,平均孔喉半径0.13 μm ,最大进汞饱和度仅55.0%,含油级别为油斑。源-储共生和源-储间隔型储层同样具有该特征,可见较好孔隙结构的储层更有利于原油富集。

综合来看,源-储紧邻型储集条件好于源-储共生型和源-储间隔型。致密(低渗)砂岩储层物性和孔隙结构决定了各源-储组合内部的油气聚集次序,油气优先富集于物性和孔隙结构较好的储层“甜点”段。

4 致密(低渗)油差异富集模式

基于临南洼陷沙三中亚段—沙四上亚段不同源-储组合类型的含油性统计和“源、压、输、储”差异富集条件的分析(表1),笔者建立了3种致密(低渗)砂岩油差异富集模式。

4.1 强供烃-强动力-高效充注-储集控富模式

该富集模式对应源-储共生型组合,主要分布在沙三中亚段、沙三下亚段上部的烃源岩层内,属于源内富集,油源充足,运聚动力强,油气在源-储剩余压力差驱动下通过孔隙和裂缝从烃源岩充注进入相邻储层运移,受储层非均质性影响,优先在厚层、优质储层内聚集(图13)。油气富集规模主要受控于储集条件,储

层发育厚度大、质量好时形成源-储互层强富集;储层发育厚度较小时,一般形成夹层较强富集。

4.2 较强供烃-差异动力-联合输导-多元控富模式

该富集模式对应源-储紧邻型组合,主要分布在沙三中亚段—沙三下亚段的非烃源岩层段内,属于源外富集,供烃条件整体较好,内部运聚动力变化大,油气从烃源岩层排出后在超压驱动下向剩余压力较小的储层段运移,并且随着源-储距离增大,动力不断衰减;若储层与烃源岩直接接触,油气通过孔缝输导充注进入储层;若不直接接触,则需通过断裂、砂体等进行运移。利用包裹体测温结合埋藏史-热史模拟可知,研究区致密(低渗)砂岩油主成藏期为馆陶晚期至今,油气运移过程与断裂活动期匹配良好^[32](图14)。由于相较于其他源-储组合其储层储集能力更优,油气经过运移后优先在物性和孔隙结构较好的储层“甜点”段聚集(图13)。在该模式下油气富集受到供烃、动力、输导、储集等多种因素控制明显,邻近优质烃源岩层或油源断裂的储层“甜点”段是有利勘探目标。亚类中,源间型整体富集条件最优,含油性最好,形成源间强富集,源上型和源下型则形成较强富集。

4.3 弱供烃-弱动力-断砂输导-输储控富模式

该富集模式对应源-储间隔型组合,主要分布在沙四上亚段的非烃源岩层内,同样属于源外富集,由于

表1 临南洼陷不同源-储组合类型含油性和油气富集条件对比

Table 1 Comparison of oil-bearing properties and accumulation conditions of the various source rock-reservoir assemblages in the Linnan Sub-sag

源-储组合类型		源-储共生型	源-储紧邻型	源-储间隔型
含油性	油气显示比例/%	28.0~100.0	9.0~78.0	2.5~25.0
	含油饱和度/%	22~83	17~75	2~51
	平均日产油量/t	11.4	6.4	1.1
供烃条件	平均烃源岩厚度/m	180.6	100.9	66.9
	优质烃源岩占比/%	70.0	70.0	42.8
运聚动力条件	源-储剩余压力差/MPa	3.0~16.9	—	—
	源-储剩余压力梯度/(MPa/km)	—	18~465	5~60
输导条件		孔缝输导	孔缝-断裂-砂体联合输导	断裂-砂体输导
	砂体平均累计厚度/m	43.8	75.7	72.9
	单砂体厚度/m	>5	0~6	0~6
储集条件	平均孔隙度/%	9.6	12.5	8.5
	渗透率中值/($10^{-3} \mu\text{m}^2$)	0.50	0.58	0.32
	孔隙特征	次生溶蚀孔和晶间孔增多	残余粒间孔和次生溶蚀孔为主	次生溶蚀孔和晶间孔增多

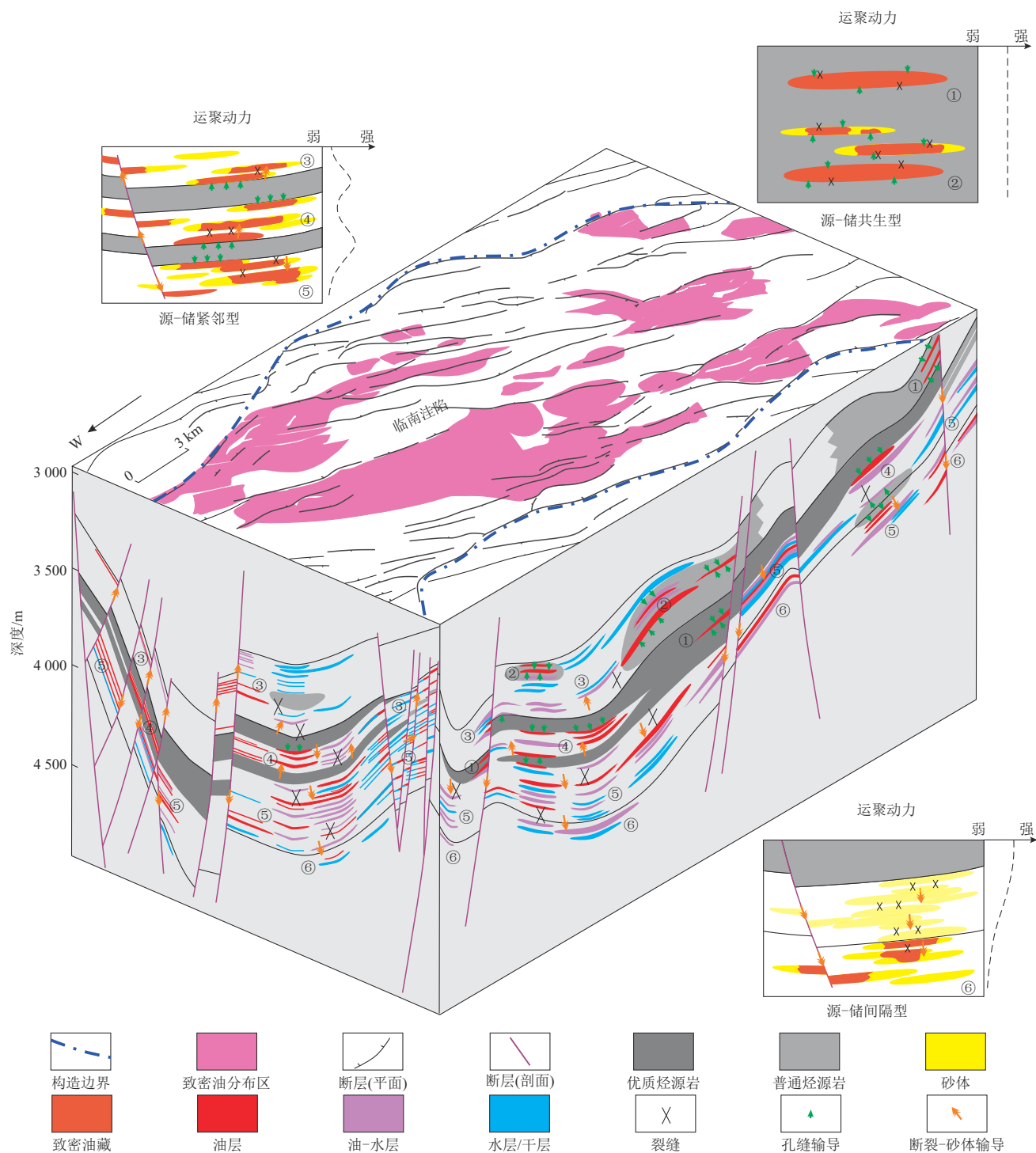


图13 临南洼陷沙三中亚段—沙四上亚段致密(低渗)砂岩油富集模式

Fig. 13 Oil enrichment model of tight (low-permeability) sandstone reservoirs in the middle submember of the 3rd member to the upper submember of the 4th member of the Shahejie Formation in the Linnan Sub-sag

- ①源-储共生夹层较强富集;②源-储共生互层强富集;③源-储紧邻源上较强富集;④源-储紧邻源间强富集;⑤源-储紧邻源下较强富集;
⑥源-储间隔源下弱富集

源、储之间存在间隔层系,源、储距离增大(图13),整体供烃条件较差,油气运聚滞后于源-储共生型和源-储紧邻型,并且油气经长距离运移后动力大量消耗,在此条件下有效输导通道和优质储层发育对于油气成藏

至关重要,得益于断裂活动期与油气运移过程的良好匹配(图14),油源断裂和垂向叠置砂体发育地区的储层“甜点”段是致密(低渗)油有利富集区,往往只在局部形成源下弱富集。

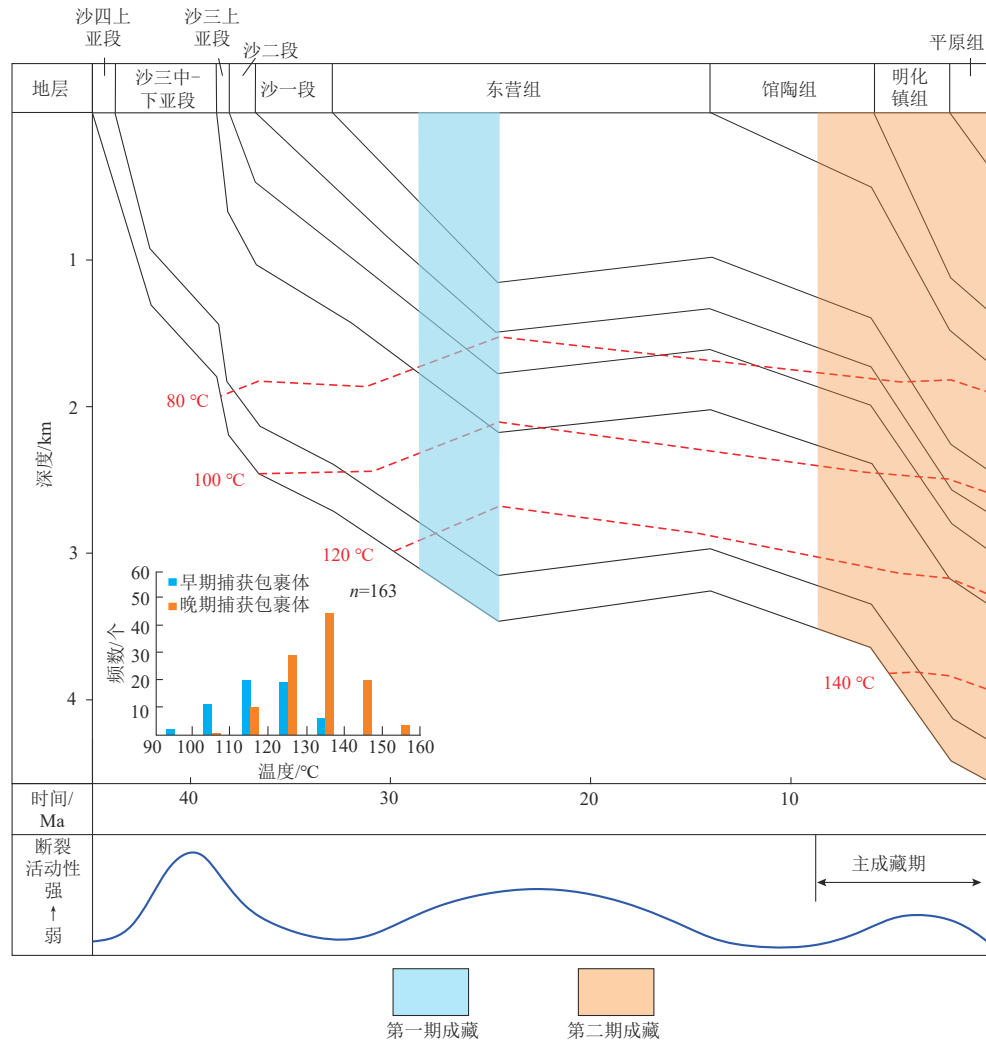


图14 临南洼陷致密(低渗)砂岩油成藏期与断裂活动匹配关系

Fig. 14 Matching relationship between the accumulation stages of oil in tight (low-permeability) sandstone reservoirs and faulting activity in the Linnan Sub-sag

5 结论

1) 临南洼陷沙三中亚段—沙四上亚段存在源-储共生型(夹层型、互层型)、源-储紧邻型(源上型、源间型和源下型)、源-储间隔型(源下型)3大类6亚类源-储组合类型。源-储共生型整体含油性最好,源-储紧邻型次之,源-储间隔型较差;亚类中以源-储共生互层型和源-储紧邻源间型含油性最好。

2) 源-储共生型具有最好的供烃条件和运聚动力条件,油气通过孔缝输导高效充注,砂体厚度制约了夹层型亚类油气富集规模;源-储紧邻型具备较好的供烃条件,运聚动力变化大,油气通过孔缝-断裂-砂体联合输导,优先充注物性和孔隙结构好的储层,油气富集受多因素控制,源间型亚类富集条件优于源上型和源下型;源-储间隔型整体供烃和运聚动力较弱,有效

输导通道和优质储层发育对于油气富集至关重要。

3) 建立了临南洼陷3种致密(低渗)砂岩油富集模式:强供烃-强动力-高效充注-储集控富模式、较强供烃-差异动力-联合输导-多元控富模式和弱供烃-弱动力-断砂输导-输储控富模式。

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