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苏北盆地高邮凹陷深层戴南组一段三亚段油气富集特征

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摘要:苏北盆地高邮凹陷深层戴南组一段(以下简称戴一段)三亚段下方为阜四段优质烃源岩,是极具潜力的资源接替层系,但其埋藏深、失利井多、构造储备圈闭少,长期以来形成了“难成藏、没潜力、没效益”的传统认识。为了明确戴一段三亚段的成藏关键和勘探潜力,综合钻井、测井、录井、实验、地震等资料,开展了层序地层、沉积体系、储盖组合、圈闭类型、成藏主控因素等多方面的基础研究。研究表明:戴一段三亚段是高邮凹陷断坳—断陷转换初期沉积的首套地层,特殊的地层发育位置使其具有“近源区盖、北洲南扇、孔缝双储、二元控藏”的油气富集特征。具体表现为6个方面:①戴一段三亚段顶部发育稳定的湖侵域泥岩,是独立的成藏单元;②戴一段三亚段下方为阜宁组四段烃源岩,位于阜宁组四段成熟烃源岩范围内,是戴南组供烃最充足的亚段;③北部缓坡带发育大型三角洲,南部陡坡带发育各类扇体,砂体发育程度呈东高西低的特征;④除构造圈闭外,还发育4种隐蔽圈闭类型,隐蔽圈闭个数多、规模大;⑤发育孔隙和裂缝两类储集空间;⑥侧向封堵和有效储层是成藏主控因素。研究新认识带来了该层系勘探思路的两大转变,指明了勘探方向,部署一批探井获得成功,推动高邮凹陷戴一段三亚段成为苏北盆地重要的资源接替阵地。

关键词:苏北盆地;高邮凹陷;戴南组深层;戴一段三亚段;主控因素;油气富集特征;隐蔽油气藏

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Oil and gas accumulation characteristics of the third submember of the first member of Dainan Formation in deep layers of Gaoyou Sag, Subei Basin

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Abstract: The third submember of the first member of Dainan Formation in the deep layers of Gaoyou Sag, Subei Basin, which overlies high-quality source rocks of the fourth member of Funing Formation, serves as a potential replacement for oil and gas resources. However, due to its deep burial depth, numerous failed wells, and limited structural reservoir traps, it has long been perceived as “difficult for accumulation, unpromising, and unprofitable”. To clarify the key factors for oil and gas accumulation and the exploration potential of the third submember of the first member of Dainan Formation, using drilling, well logging, mud logging, experimental data, and seismic data, fundamental studies were conducted on multiple aspects, including sequence stratigraphy, sedimentary systems, reservoir-seal combination, trap types, and main controlling factors of oil and gas accumulation. The results showed that the third submember of the first member of Dainan Formation was the first sedimentary strata at the early stage of the transition from fault sag to fault subsidence in Gaoyou Sag. Its unique stratigraphic development position endowed it with oil and gas accumulation characteristics of “near-source sealing, northern delta and southern fan, dual pore-fracture reservoirs, and dual control on reservoirs”. Specifically, it was manifested in six aspects: (1) The top of the third submember of the first member of Dainan Formation was characterized by stable transgressive lacustrine mudstone, serving as an independent oil and gas accumulation unit. (2) Underlying the third submember of the first member of Dainan Formation, the fourth member of Funing Formation was located within the mature source rock zone, making it the most oil and gas-rich submember in Dainan Formation. (3) A large delta developed in the northern gentle slope and various types of fan bodies in the southern steep slope. The sand body development showed an east-high-west-low distribution pattern. (4) In addition to structural traps, four types of subtle traps developed abundantly in large scale. (5) Two types of reservoir spaces—porosity and fractures—developed. (6) Lateral sealing and effective reservoirs were the main controlling factors for

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reservoir formation. The findings from the research brought two major shifts in exploration strategies for this stratigraphic sequence, identified exploration directions, and led to successful drilling of multiple exploration wells. This promotes the third submember of the first member of Dainan Formation in Gaoyou Sag to become an important resource replacement area in Subei Basin.

Keywords: Subei Basin; Gaoyou Sag; deep layer of Dainan Formation; third submember of the first member of Dainan Formation; main controlling factors; oil and gas accumulation characteristics; subtle oil and gas reservoirs

戴南组是苏北盆地高邮凹陷主力勘探层系之一,戴南组一段(以下简称戴一段)三亚段位于戴南组底部,下方为阜宁组四段(以下简称阜四段)主力烃源岩,埋深普遍大于3 000 m。早期勘探受成藏认识和工程技术的限制,戴南组勘探主要集中在中浅层的戴一段一、二亚段和戴南组二段(以下简称戴二段),在富民构造、真武断裂带、汉留断裂带等有利构造带发现了油田,但经过多年的勘探开发,探明程度已较高,效益与规模增储难度越来越大。对于深层戴一段三亚段这个邻源层系,早期按照常规思路探索构造高带上的断鼻圈闭,但钻井均落空,长期以来形成了“难成藏、没潜力、没效益”的传统认识。戴一段三亚段和戴一段二亚段属于戴一段一亚段区域盖层控制下同样的成藏单元,因此也未对深层戴一段三亚段开展过系统研究。

深层—超深层已成为中国中西部盆地油气勘探的重要领域^[1-6],随着东部断陷盆地中浅层油气藏勘探开发程度越来越高,多个拗陷逐步向深层探索,如济阳拗陷、冀中拗陷、辽河拗陷^[7-12]。深层的研究对于高邮凹陷同样至关重要,其深层的戴一段三亚段紧邻烃源岩,但埋深较大、成藏主控因素不清、构造储备圈闭少等一系列问题造成该层系勘探潜力与方向不明,严重制约了勘探进程。通过系统研究戴南组深层层序地层、石油地质条件、成藏特征、主控因素,发现了戴一段三亚段新储盖组合,明确了其油气富集特征,从而指出了有利勘探方向,为戴一段三亚段勘探突破提供了有力支撑。

1 区域地质特征

高邮凹陷是苏北盆地油气最富集的拗陷,位于苏北盆地南部的东台拗陷中部,呈北东向长条形分布,南为苏南隆起,北接柘垛低凸起与建湖隆起相连,东起白驹拗陷,东南靠吴堡低凸起与溱潼拗陷相连,西接菱塘桥低凸起与金湖拗陷相隔,受控于南部的边界大断层,总体结构呈南断北超的箕状断陷结构,由南向北依次划分为南部陡坡带(断阶带)、中央深凹带、北部缓坡带(斜坡带)3个次级构造单元^[13-16]。南部真①-吴①断裂是高邮凹陷与苏南隆起、吴堡低凸起的分界,北部汉留断裂是深凹带与缓坡带的分界,拗陷中西部属双断地堑式断陷结构,东部由于汉留断层不发育,斜坡与深凹无明显分界,属单断单斜式断陷结构(图1a)。

高邮凹陷新生界沉积厚达7 000 m,是苏北盆地沉降最深的拗陷,自下而上沉积了泰州组、阜宁组、戴南组、三垛组、盐城组、东台组。戴南组由下至上可分为戴一段和戴二段。自下而上戴一段进一步分为3个亚段,戴二段分为5个亚段(图1b)。戴南组是高邮凹陷进入断陷阶段之后沉积的一套地层,与下伏阜宁组烃源岩呈角度不整合接触,各亚段逐层充填超覆沉积在区域不整合面上,深凹带地层厚度近2 000 m,北部缓坡带逐渐减薄(图2)。

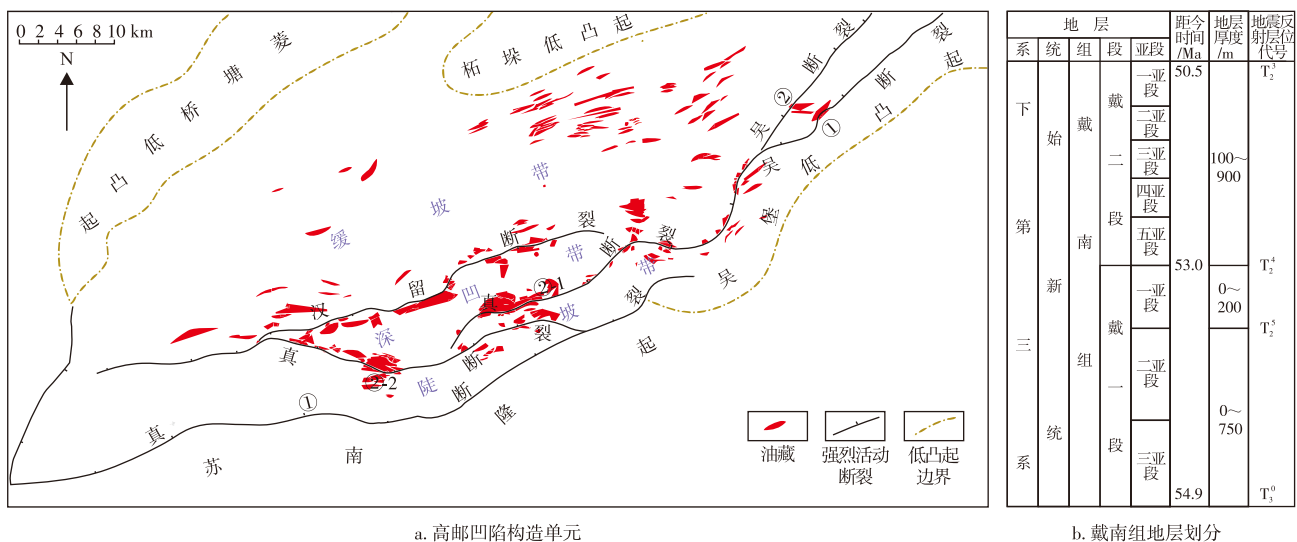


图1 高邮凹陷构造单元和戴南组地层划分

Fig. 1 Structural unit division of Gaoyou Sag and stratigraphic division of Dainan Formation

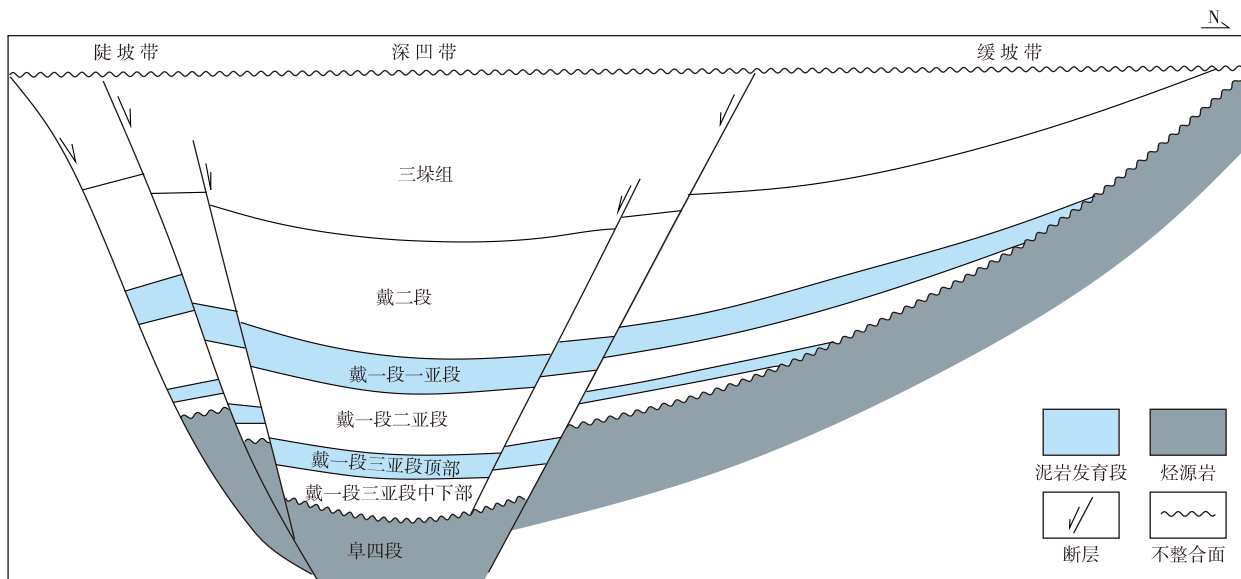


图2 高邮凹陷戴南组与阜宁组接触关系模式

Fig. 2 Contact relationship patterns between Dainan and Funing Formations in Gaoyou Sag

戴南组历经多年勘探,戴二段和戴一段中上部已基本连片含油,进入评价勘探阶段。而戴南组底部埋藏最深的戴一段三亚段,勘探程度较低、仅有零星发现,分析认为戴南组深层戴一段三亚段成藏条件优越,是重要的资源接替领域。

2 油气富集特征

戴一段三亚段是高邮凹陷断坳—断陷转换初期沉积的首套地层,特殊的地层发育位置使高邮凹陷戴一段三亚段具有“近源区盖、北洲南扇、孔缝双储、二元控藏”的油气富集特征,勘探潜力大。

2.1 近源区盖

1) 苏北盆地古近纪早期(阜宁组沉积时期)为统一湖盆的断坳阶段,沉积了苏北盆地阜宁组二段、阜四段两大主力烃源岩,岩性为深一半深湖深色泥岩、泥灰岩^[17]。阜四段烃源岩为断坳期最后沉积的一套地层,之后始新世末期的吴堡运动,盆地整体抬升,原来处于水下的高地也随之出露水面,断裂加剧活动,致使阜宁期统一的沉积盆地分解成凹凸相间的凸起、低凸起和凹陷,然后进入了渐新世时期以强烈断陷为主的充填阶段。从高邮凹陷戴南组与阜宁组接触关系模式图来看,戴一段三亚段是断陷阶段最早沉积的一套地层,下面为阜四段烃源岩,位于阜四段成熟烃源岩范围内,具备优先充注的有利条件,是戴南组供烃最充足的层段(图2)。

2) 前人研究认为戴一段只发育一套稳定盖层^[18-20],即戴一段一亚段“五高导泥岩”,高导泥岩与下方砂岩发育段戴一段二亚段、三亚段组合形成了非常有利的储盖

组合,戴一段二亚段、三亚段纵向上属于同一个成藏单元,由于储层发育段厚度大,上部紧贴盖层的戴一段二亚段是主探层,下方的戴一段三亚段一直未受重视。通过层序地层研究,戴一段二亚段、三亚段是完整的低位域—湖侵域—高位域沉积旋回,戴一段三亚段包含低位域—湖侵域,其中下部为低位域、顶部为湖侵域。戴一段三亚段顶部湖侵域泥岩段虽然薄(平均厚度介于20~60 m),但是区域稳定,是良好的区域性盖层,与低位域砂岩形成良好的储盖组合(图3)。新储盖组合的发现意义重大,带来了高邮凹陷戴一段三亚段是独立成藏单元的新认识,勘探前景广阔。

2.2 北洲南扇

1) 前人针对戴南组沉积相研究集中在戴一段三亚段以上地层^[21-28],底部戴一段三亚段研究较少。研究表明:戴一段三亚段为断陷早期的充填沉积,湖盆窄、水体浅,北部缓坡带发育大型三角洲,南部陡坡带发育各类扇体。北物源缓坡带三角洲沉积体系东西差异大,东部来自北物源的三角洲砂体分布范围广,如花庄地区、富民、永安等地区,主要发育三角洲前缘亚相,岩性为浅灰色粉砂岩与浅灰色、棕色泥岩互层,砂岩累计厚度介于10~90 m,砂地比介于30%~70%。大型三角洲在向前推进过程中分流为多个分支河道,前端发育河口坝。西部联盟庄—马家嘴地区不发育大型三角洲,砂体发育程度低,以薄砂、泥岩为主。南物源陡坡带受上升盘母源和古地貌的影响,自东向西发育多类型扇体:周庄南—徐家庄地区发育泥扇、富民—肖刘庄地区发育富砂型扇三角洲、真武—曹庄地区发育富砾型扇三角洲、邵伯地区发育近岸水下扇、黄珏地区发育富砾型扇三角洲。戴一段三亚段整体表现为“北洲南扇、东大西小”的沉积格局(图4)。

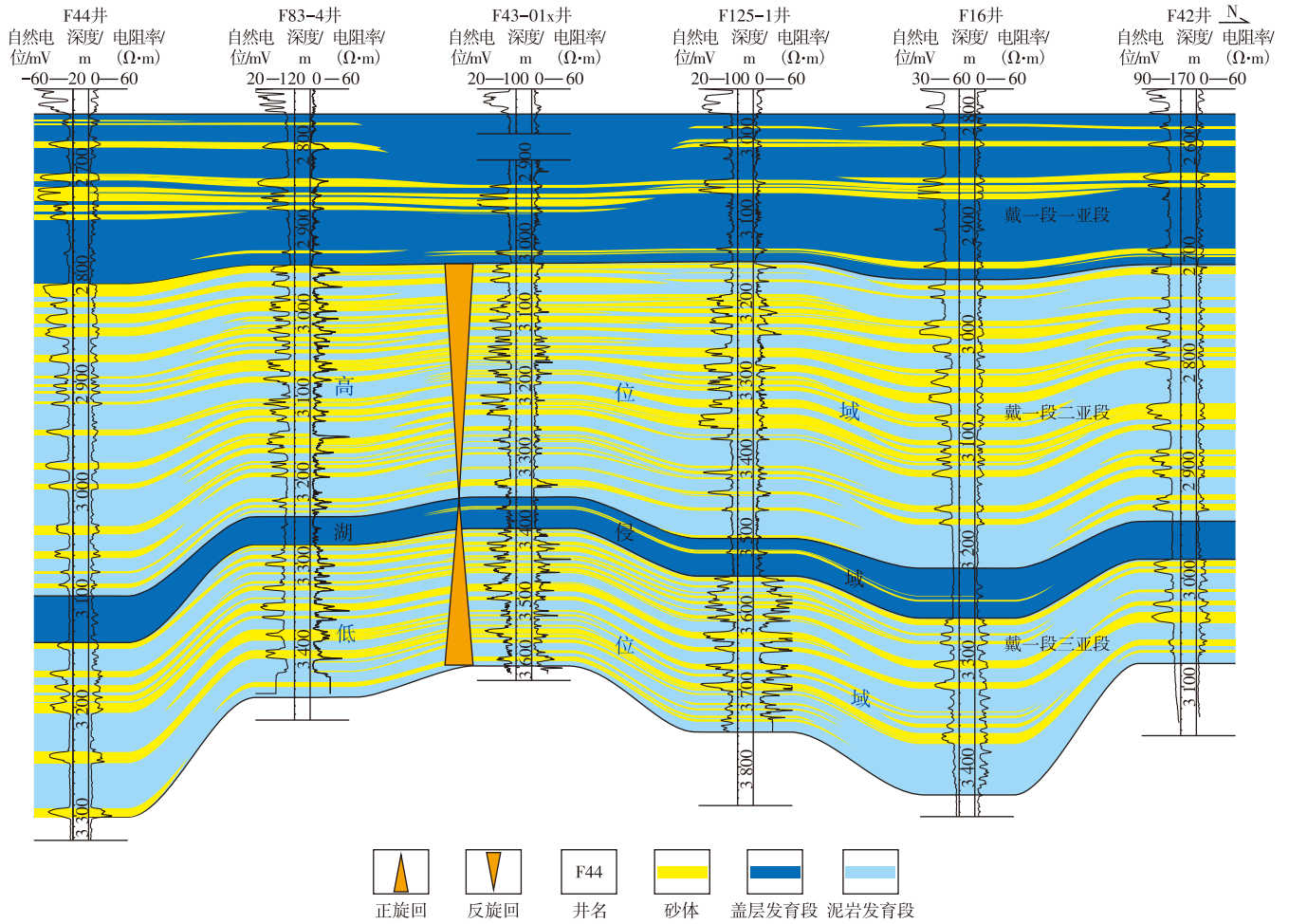


图3 高邮凹陷戴一段连井剖面

Fig. 3 Cross-section of wells in the first member of Dainan Formation in Gaoyou Sag

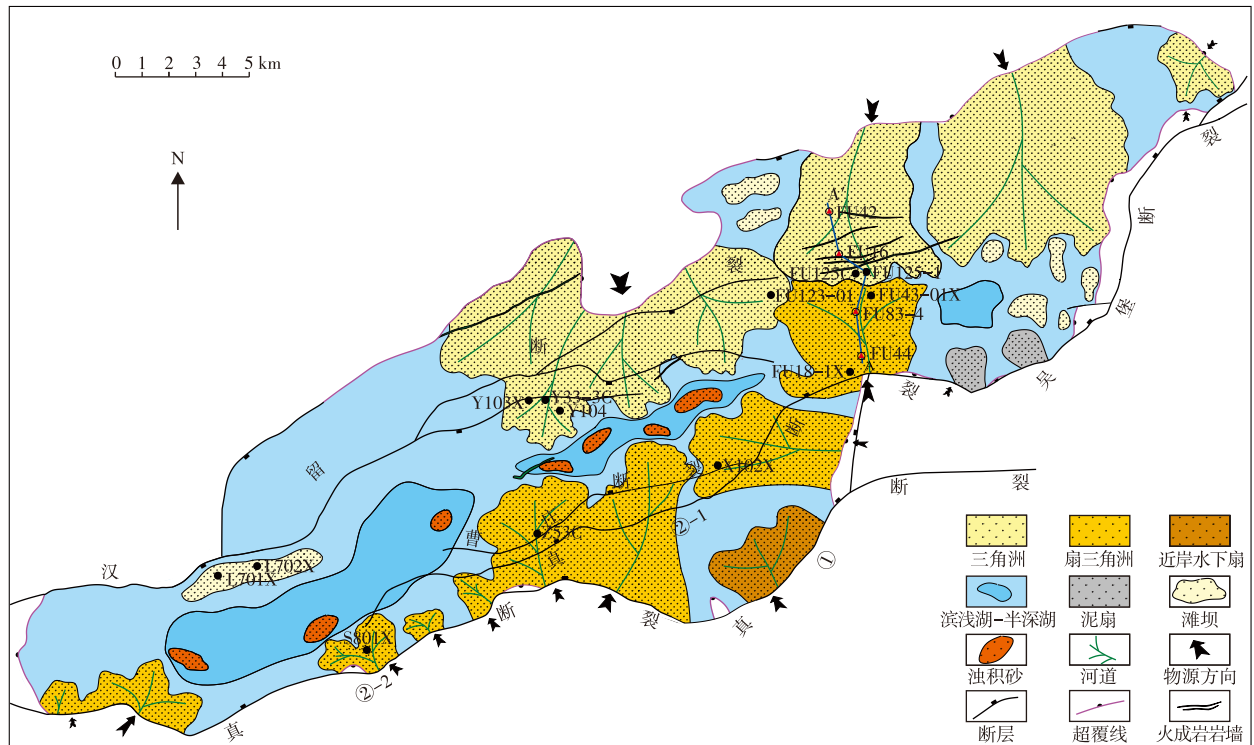


图4 高邮凹陷戴一段三亚段沉积相

Fig. 4 Sedimentary facies map of the third submember of the first member of Dainan Formation in Gaoyou Sag

2) 之前按照常规思路,针对戴一段三亚段构造高带上非常落实的断鼻圈闭、埋藏浅的地层超覆都有井钻探,但没有取得预期成效,戴一段三亚段可勘探的储备圈闭已经非常少,形成了该层系无潜力的固有认识。研究认为除构造型(顺向断层型、反向断层型)、地层超覆型等传统类型外,在北洲南扇沉积体系、断裂格局、火成

岩的控制下,戴一段三亚段还发育岩墙遮挡型、顺向断层-河道型、顺向断层-扇控型、透镜型(滩坝-浊积岩)4种隐蔽圈闭类型(图5)。通过圈闭精细识别与评价发现隐蔽圈闭个数多、规模大,勘探潜力大。研究结果打破了戴一段三亚段“构造圈闭少、勘探无潜力”的传统认识。

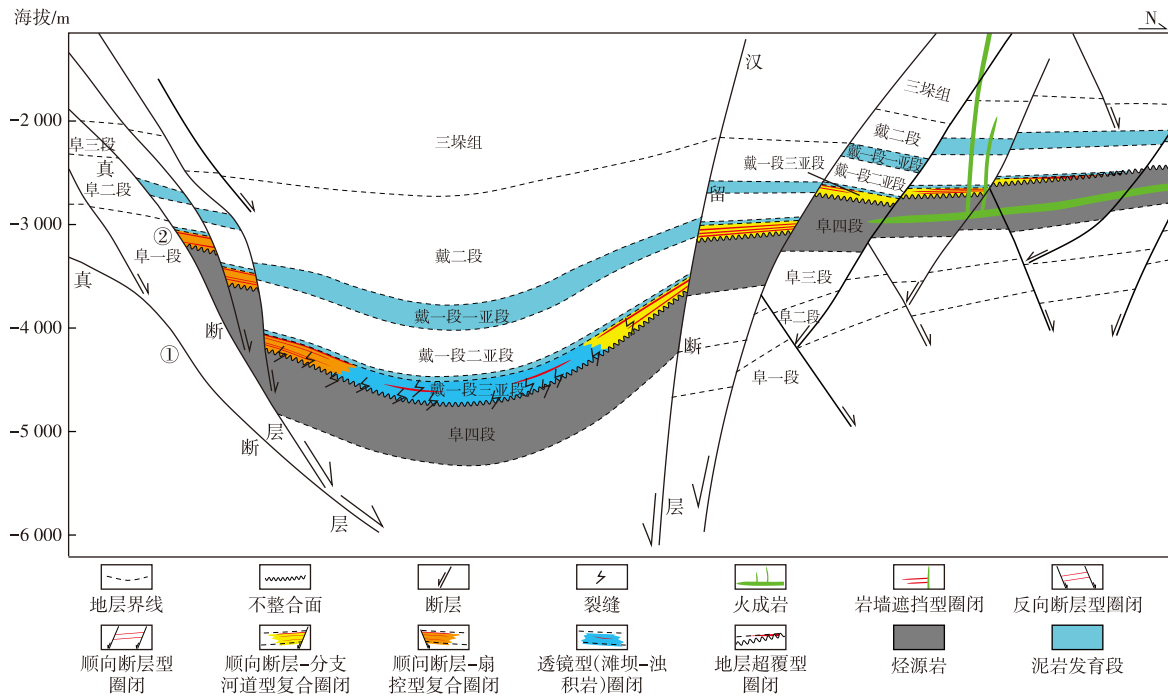


图5 高邮凹陷戴一段三亚段圈闭模式

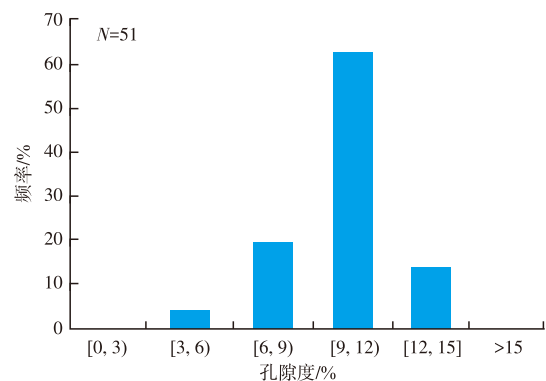
Fig. 5 Trap patterns of the third submember of the first member of Dainan Formation in Gaoyou Sag

2.3 孔缝双储

高邮凹陷戴一段三亚段储集类型以三角洲前缘水下分支河道和河口坝、扇三角洲前缘水下分支河道和河口坝各类砂岩为主。戴一段三亚段作为戴南组最底部的地层,与阜四段不整合接触,断坳-断陷转换初期特殊的纵向位置使其储集空间可以分为孔隙和裂缝两大类。从F125-3井的取心实测数据来看,在埋深3 500 m的情况下,孔隙度平均值仍然为9.4%(图6)。镜下照片分析表明:①孔隙以原生粒间孔、粒内溶孔、粒间溶孔为主,原生孔隙和次生孔隙均发育(图7a、图7b);②裂缝较为发育,多为高角度裂缝、近90°垂直地层、多见X型剪切型裂缝组合样式、裂缝面呈水平擦痕,裂缝长度最大超过1 m;③裂缝密度最大约19条/m(图8)。在“孔缝双储”储集条件的控制下,戴一段三亚段的油气富集可以打破物性限制,虽然埋藏深,仍可获得高产稳产。

2.4 二元控藏

从油气成藏的要素“生储盖圈运保”来看,戴一段三亚段油源、盖层、圈闭、运移均为有利条件,但成藏的关键

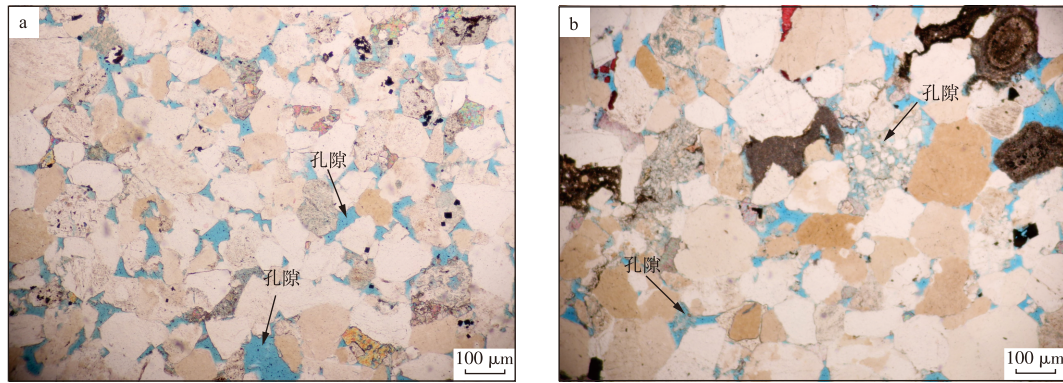


注:N为样本数。

图6 高邮凹陷戴一段三亚段F125-3井孔隙度与频率关系

Fig. 6 Relationship between porosity and frequency at well F125-3 in the third submember of the first member of Dainan Formation in Gaoyou Sag

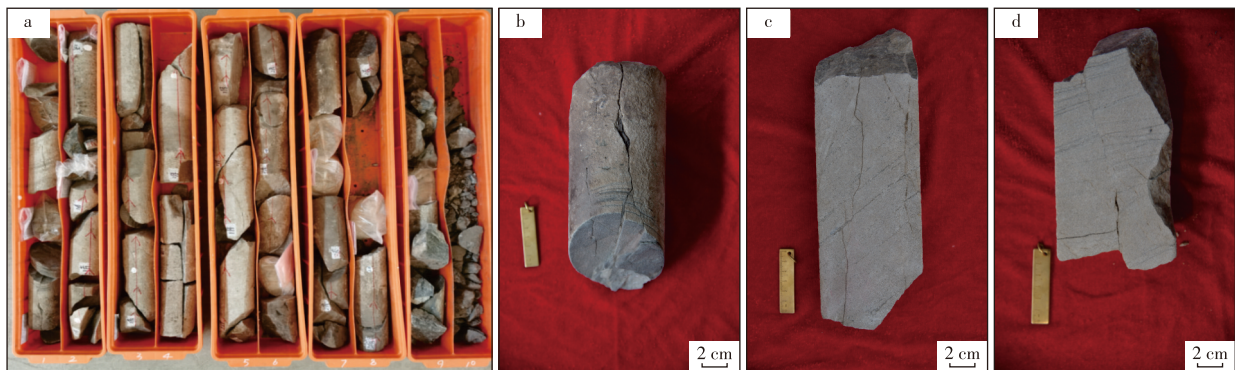
在于封堵和储层,封堵差和储层不利是前期钻井失利的主要原因。戴一段三亚段砂体展布东西差异大,东厚西薄。东部发育的大型三角洲、扇三角洲控制了10~90 m厚砂体,西部发育的小型扇三角洲、滩坝、浊积砂控制了2~4 m单层薄砂体。东厚西薄的砂体展布特征与断裂格局、地层产状共同控制下,形成了“封堵+储层”的二元控



注:a.深度3580.53 m,孔隙分布略不均匀,以原生粒间孔、粒间溶孔为主,颗粒间线接触为主,略具定向排列,溶蚀现象普遍,原生粒间孔形态呈三角形、多边形等,孔隙边缘平直;b.深度3580.53 m,孔隙分布略不均匀,溶蚀现象普遍,粒间溶孔形态呈不规则状、多边形等,孔隙边缘见明显的溶蚀现象。

图7 高邮凹陷戴一段三亚段F125-3井碎屑岩储层镜下特征

Fig. 7 Microscopic characteristics of clastic reservoirs at well F125-3 in the third submember of the first member of Dainan Formation in Gaoyou Sag



注:a.深度介于3579.2~3592.5 m;b.深度3579.2 m,发育裂隙与小错断;c.深度3580.07 m,灰色中一细砂岩,发育泥质条带和低角度交错层理,裂隙较发育;d.深度3586.08 m,灰色中细砂,可见平行层理和高角度裂缝。

图8 高邮凹陷戴一段三亚段F125-3井第一筒取心岩相及裂缝特征

Fig. 8 Lithofacies and fracture characteristics of the first core at well F125-3 in the third submember of the first member of Dainan Formation in Gaoyou Sag

藏特征。

1) 高邮凹陷受多期构造作用改造,断裂体系发育,与砂体形成的断-砂输导体系既为油气的运移提供了条件,也造成了油气的逸散。富民、花庄、真②-1断层上升盘、汉留断层上升盘等地区砂体基本连片,断裂发育,储层条件优越,侧向封堵是圈闭成藏的关键。对于反向断块,目的盘戴一段三亚段极易与封堵盘砂岩发育的戴一段二亚段对接,形成砂-砂对接,油气封挡能力较差,如构造背景上圈闭落实的F13断块、F5断块均因侧向封挡条件不利而落空。但当断距较适中时,目的盘戴一段三亚段与封堵盘戴一段一亚段、封堵盘戴一段三亚段顶泥岩对接,形成砂-泥对接,大大提高了油气侧向封挡的有效性(图9a、图9b)。对于顺向断块而言,戴一段三亚段可以与阜四段泥岩对接,封挡条件有利(图9c)。另外,高邮凹陷发育陡立火成岩岩墙,可以形成纵向多层系全封堵的火成岩岩墙遮挡型圈闭,侧向封挡条件最好(图9d)。

2) 在封堵有利的前提下,储层厚度越大,油气越富集。汉留断层下降盘、真武断层下降盘等深凹带和永安以西等地区,发育三角洲前缘、前三角洲、扇三角洲前缘、前扇三角洲等亚相,砂体横向变化快或砂地比低,平面上呈朵叶状连排分布,砂体被顺向断层切割,形成了顺向断层-分支河道型圈闭和顺向断层-扇控型圈闭。该类圈闭邻近深凹带,受顺向断层控制,具有近源供烃、侧向封挡能力强的优越成藏条件。但该类圈闭受沉积相带的控制,砂体横向变化较快,向深凹带和两侧快速尖灭,因此其圈闭规模与富集受岩性的控制,其中三角洲前缘和扇三角洲前缘亚相的分支主河道储层物性条件相对较好,是油气富集有利相带。

3) 戴一段三亚段东西部成藏主控因素不同。东部和断裂带砂体连片发育、小断层多,形成封堵主控,这些地区不缺砂体,只要封堵条件有利就能成藏。环深凹带和西部顺向断层发育、砂体横向变化快、砂地比低,形成

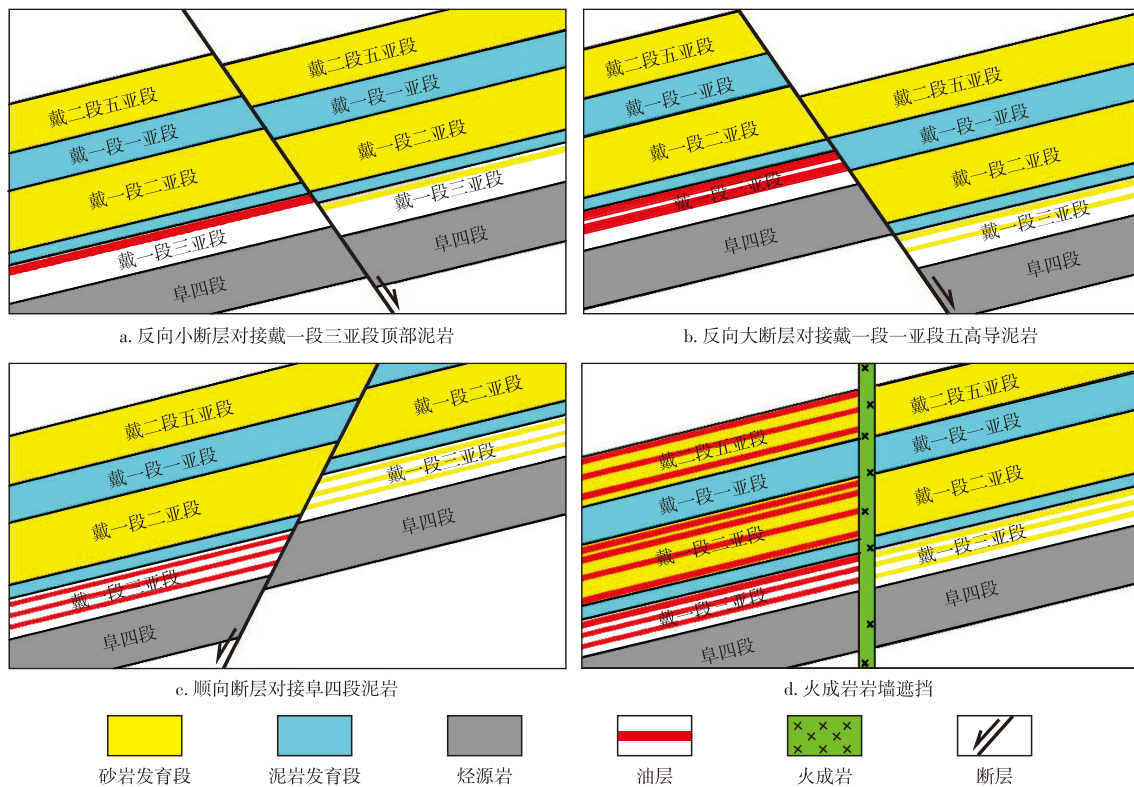


图9 高邮凹陷戴一段三亚段有利封堵类型模式

Fig. 9 Favorable sealing patterns in the third submember of the first member of Dainan Formation in Gaoyou Sag

储层主控,这些地区整体保存条件好,有砂均能成藏,砂体越发育,油层越富集。即对于区带而言,东部和断裂带找构造,评价封堵;西部和环凹带找隐蔽,评价储层。

3 勘探实践

高邮凹陷戴一段三亚段成藏的新认识,带来了两点勘探思路的转变,并有力地指导和支撑了勘探实践。

1) 由找“反向块”转向找“顺向块、岩墙”:侧向封堵决定了有利圈闭类型,高邮凹陷戴一段三亚段苛刻的封堵条件,反向断块一般封堵差,岩墙遮挡型圈闭、顺向断层型圈闭、反向大断距圈闭等封堵有利的圈闭类型是首选勘探目标。在此认识的指导下,针对岩墙遮挡型圈闭部署F125c井,实现了戴一段三亚段的首次突破。之后针对顺向断块圈闭部署F18-1井,针对反向大断距圈闭部署F123-01井,相继获得成功。

2) 由找“构造”转向找“隐蔽”:戴一段三亚段构造储备圈闭少,封堵有利的储备圈闭更少,但储层主控的隐蔽油气藏勘探程度低、储备圈闭多,寻找储层厚度大、物性好的隐蔽油藏是下一步勘探重点。针对北物源分支河道型隐蔽圈闭,部署永扇控型隐蔽油气藏Y33-3c、Y103、Y104等井;针对南物源的扇控型隐蔽圈闭,部署Z53c、S801、X18、C101等井。

基于研究认识部署的十几口井均获得成功,实现了

高邮凹陷戴南组深层戴一段三亚段勘探突破,戴一段三亚段已成为苏北盆地重要的资源接替领域。

4 结论

1) 高邮凹陷戴一段三亚段发育多类型储层,顶部为稳定的湖侵域泥岩区域盖层,下方为阜四段烃源岩。戴一段三亚段为独立的成藏单元,是苏北盆地资源接替的重要领域。

2) 高邮凹陷戴一段三亚段虽然构造圈闭少,但分支河道型、扇控型、透镜型、岩墙遮挡型等隐蔽圈闭发育,是下一步重点勘探类型。

3) 高邮凹陷戴一段三亚段虽然埋深普遍大于3 000 m,但次生孔隙与裂缝发育为油气富集提供了有利的储集空间。

4) 高邮凹陷戴一段三亚段具有“近源区盖、北洲南扇、二元控藏、孔隙双储”的油气成藏特征,“封堵+储层”控制了其油气富集。主要勘探方向是东部和断裂带找构造,评价封堵;西部和环凹带找隐蔽,评价储层。

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