渤海湾盆地南堡凹陷南部深层沙一段优质碎屑岩储层特征及成因机制

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内容提要：利用岩芯、薄片、扫描电镜和分析化验等资料，对南堡凹陷南部深层古近系沙一段（沙河街组一段）优质碎屑岩储层特征进行了分析并揭示其成因机制。研究表明：①南堡凹陷南部沙一段优质碎屑岩储层属于低孔中渗储层，发育原生孔隙、次生孔隙和微裂缝；②沙一段沉积期处于强水动力沉积环境，辫状河三角洲前缘水下分流河道砂体普遍发育，岩性主要为中粗砂岩、含砾砂岩和砂砾岩等粗岩性，岩石类型主要为岩屑长石砂岩，石英、岩浆岩岩屑等刚性组分含量高，储层在强压实作用下仍保留了局部原生残余粒间孔，部分刚性组分强压条件下形成微裂缝；③沙一段与东三段为区域不整合接触，大气水的酸性流体在成岩初期以及烃源岩成熟之后产生的有机酸在成岩后期通过油源断裂和不整合面进入储层，造成长石、易溶碎屑等组分溶蚀形成次生孔隙，溶蚀作用不仅增加孔隙空间，而且扩大喉道宽度。结论认为：粗岩性和高刚性颗粒含量为原生孔隙的保存提供了物质基础；油源断层、不整合面为酸性流体的进入提供路径，促进了次生孔隙发育。

关键词：渤海湾盆地；南堡凹陷南部；沙一段（沙河街组一段）；优质碎屑岩储层；储层特征；成因机制

受南堡凹陷中北部高柳断层的影响，在南堡凹陷中南部高柳断层的下降盘沉积了厚度较大的古近系地层，导致南堡凹陷南部古近系沙一段（沙河街组一段）与南堡凹陷北部沙三段（沙河街组三段）Ⅳ～Ⅴ油组埋深相当，埋深超过4000 m。普遍认为随着地层埋深的增加，储层物性受压实作用发生致密化而失去商业价值（戴金星等，2012；Zhou Yong et al., 2016；杨华等，2017；Lai Jin et al., 2017）。在南堡凹陷，前期勘探研究认为有效碎屑岩储层埋深下限为4000 m（郝建明和邱隆伟，2008；姜福杰等，2013；李业会等，2014），受地质认识、勘探成本、地表条件等因素限制，南堡凹陷南部深层油气勘探进展较慢。随着南堡凹陷浅层优质储量油气产量逐年降低（杨荣超等，2015），深层油气勘探成为重要的勘探目标（张善文，2006；蒋凌志等，2009；邹才能等，2010；蒋有录等，2015；罗晓荣等，2016；李威等，2021）。前人在烃源岩评价、地层、构造演化、沉积环境、油气系统分析等方面的研究表明南堡凹陷南部沙一段是有利的油气成藏层位（郑红菊等，2007；汪泽成等，2008；Dong Yuexia et al., 2010；王华等，2011；朱光有等，2011；Guo Yingchun et al., 2013；董月霞等，2014），但是否在深层超过4000 m埋深的沙一段发育优质碎屑岩储层？勘探实践证实，位于南堡凹陷南部的堡古2井在沙一段4248.0～4257.4 m钻探获得孔隙度11.7%、渗透率12.7×10^{-3} μm^2的优质碎屑岩储层，8 mm油嘴放喷自然产能为日产油118 m^3、天然气11×10^4 m^3，表明南堡凹陷南部深层发育优质碎屑岩储层，并且该储层要优于南堡凹陷北部相同埋深储层。围绕堡古2井区的勘探突破，前人开展了大量研究工作。董月霞等（2014）认为南堡凹陷南部沙一段优质储层为辫状河三角洲沉积，母岩类型、沉积环境和异常高压是储层物性控制的主导因素；赵迎东等（2018）认为南堡凹陷南部优质储层分选好、杂基含量少，储层抗压实能力强，有

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利于孔隙保存;Kashif Muhammad 等(2019)在研究南堡凹陷南部沙一段储层特征时提出粗粒砂岩发育大孔隙和连通孔隙,具有较高的孔隙度和渗透率,而细粒砂岩和粉砂岩发育大量的小孔隙,但连通性较差,具有高孔隙度和低渗透率特征;吴浩等(2019)认为南堡凹陷南部堡古 2 井区沙一段优质储层发育的主控因素为异常增孔地质作用;王恩泽等(2020)认为南堡凹陷南部沙一段优质储层的形成以抗压实保孔作用为主,溶蚀增孔作用为辅。国内外学者在沉积储层研究方面取得了丰富成果,但对于深层优质碎屑岩储层的成因机制缺乏深入分析,制约了南堡凹陷南部深层油气进一步勘探开发。本论文利用岩芯、薄片、扫描电镜和分析化验等资料,对南堡凹陷南部深层沙一段储层的储集特征进行了分析,并探讨了其成因机制,可以为渤海湾盆地类似地质条件深层油气勘探提供一定借鉴。

1 地质背景

南堡凹陷位于渤海湾盆地的北部(图 1a),面积 1932 km^2,其南部为沙垒田凸起,北部为西南庄—柏各庄凸起,按照地质特点及油气田发育特点,将南堡凹陷分为 8 个次级构造带(图 1b;周海明等,2000;Jiang Fujie et al., 2018),研究区位于南堡凹陷南部的南堡 3 号构造带(图 1c),目的层为古近系沙河街组一段(简称“沙一段”),埋深超过 4000 m。研究区沙河街组自下而上分为沙三段、沙二段和沙一段,其中:沙三段发育厚层暗色泥岩,沙二段发育薄层红色泥岩,沙一段下部为厚层暗色泥岩,上部为砂泥岩互层。沙一段与东三段之间为不整合接触,该不整合为南堡凹陷的区域性不整合(董月霞等,2014;Zhang Jianguo et al., 2017;张磊等,2018)。研究区南部为斜坡沉积背景(图 1b),长期接受南部沙垒田凸起物源供给,具有“沟槽输砂”的沉积特征,为辫状河三角洲沉积(董月霞等,2014;文雯等,2017;王恩泽等,2020)。研究区发育沙一段下部和沙三段两套优质烃源岩,均已进入生烃高峰期(Guo Yingchun et al., 2013;张顺等,2017)。沙一段储层中油源来自沙一段下部烃源岩,为Ⅱ型干酪根,有机质含量较高,镜质体反射率为 0.8%(郑红菊等,2007;朱光有等,2011)。沙一段顶部发育厚层砂岩储层,良好的“下生上储式”源—储配置关系使得沙一段成为油气勘探的重要层位。东二段上部发育的厚约 200 m 浅灰色泥岩段为南堡凹陷区域性盖层,另外在东三段发育多套 30~50 m 的深灰色、灰色泥岩段,形成了目的层段的多套局部盖层,有效保护了油气藏。与沙一段烃源岩沟通的油源断裂及沙一段与东三段之间的不整合面共同构成良好的油气运移通道(汪泽成等, 2008;颜世永等, 2010;Chen Xiangfei et al., 2016;王洪宇等,2020)。堡古 2 井是第 1 口揭露该区深层碎屑岩优质储层的风险勘探井,随后在堡古 2 井以西约 18 km 处钻探的堡探 3 井在相邻层位也获得成功(图 1b),表明南堡凹陷南部深层具有大面积连续油藏分布的可能。

2 深层碎屑岩储层基本特征

2.1 沉积特征

南堡凹陷古近系大部分地区沉积物源来自盆地东部和北部,主要以扇三角洲沉积体系为主(徐安娜等,2006;夏景生等,2017;Zhang Jiankun et al., 2019),但研究区沉积物源来自南部的沙垒田凸起(王政军等,2015;杜庆祥等,2016;图 1b),主要为辫状河三角洲沉积体系,该物源持续供给南堡凹陷南部地区,沙垒田凸起花岗岩的母岩类型为研究区沉积物刚性颗粒的富集提供了较好的物质基础。

南堡凹陷南部深层沙一段主要发育辫状河三角洲前缘的水下分流河道、水下分流间湾、河口坝和席状砂等 4 种沉积微相(董月霞等,2014)。水下分流河道的岩性主要为中粗砂岩(图 2a)、含砾砂岩(图 2a)和砂砾岩(图 2b)等粗粒岩性,垂向上粒度向上变细(图 2a、c),自然电位为钟形或箱形组合,自然伽马呈齿化箱形,深测向电阻率与浅侧向电阻率有明显幅度差(图 2k),粒度概率曲线主要为两段式(图 2i),C—M 图以 NO—OP 段为主(图 2j),搬运方式为强水动力作用的牵引流,在河道底部常见冲刷面构造(图 2c),同样反映了强水动力的沉积特点。水下分流间湾的岩性主要为深灰色泥岩(图 2d)和夹砂质条带泥岩(图 2e),自然电位曲线光滑、负异常,声波时差高,深浅侧向曲线幅差不明显。河口坝的岩性主要为灰色中砂岩、细砂岩(图 2f),碳屑发育,垂向上粒序与水下分流河道相反,为底细顶粗的反粒序特征(图 2f),自然电位呈漏斗状,自然伽马呈齿化漏斗状,深测向电阻率与浅侧向电阻率有幅度差,但幅度差小于水下分流河道(图 2l),交错层理发育(图 2g),反映了强水动力的沉积特点。席状砂的岩性粒度偏细,主要由粉砂岩、泥质粉砂岩组成(图 2h),单砂体薄,自然电位呈指状突进。研究区主要的油气储集砂体为水下分流河道与河口坝砂体,水下分流河道砂体连通性较好,多口井钻遇了

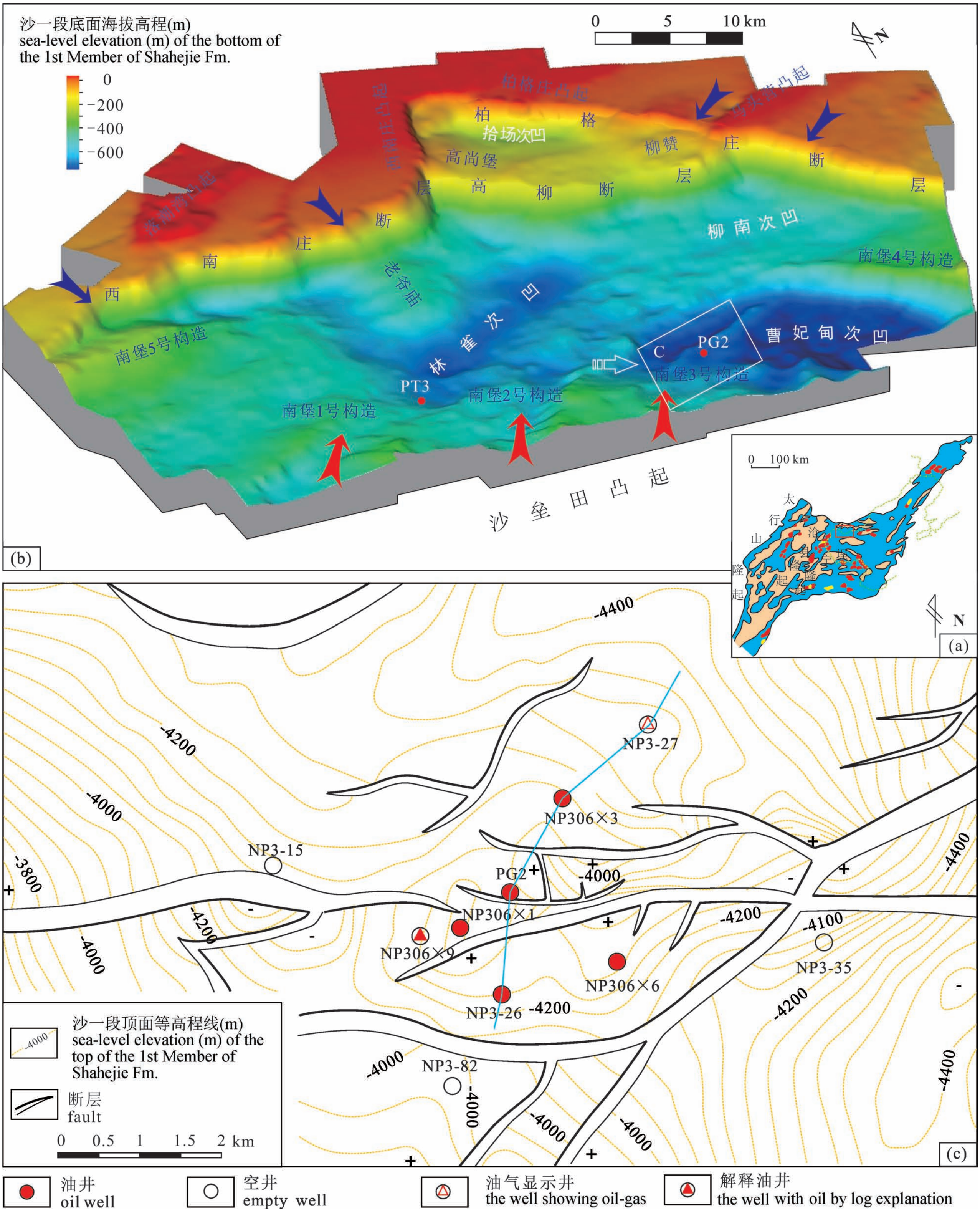

图 1 渤海湾盆地南堡凹陷南部地区综合地质图

Fig. 1 Comprehensive geological map of the southern Nanpu Sag, Bohai Bay Basin

(a)南堡凹陷位置图；(b)南堡凹陷古近系沙一段沉积期古地貌图(据王华等，2011 修改)；(c)南堡 3 号构造古近系沙一段顶面构造图

(a) locations of the Nanpu Sag; (b) palaeogeomorphologic map of sedimentary period of Paleogene Es_1 in Nanpu Sag (modified from Wang Hua et al., 2011&); (c) buried depth of Paleogene Es_1 in Nanpu No. 3 structure

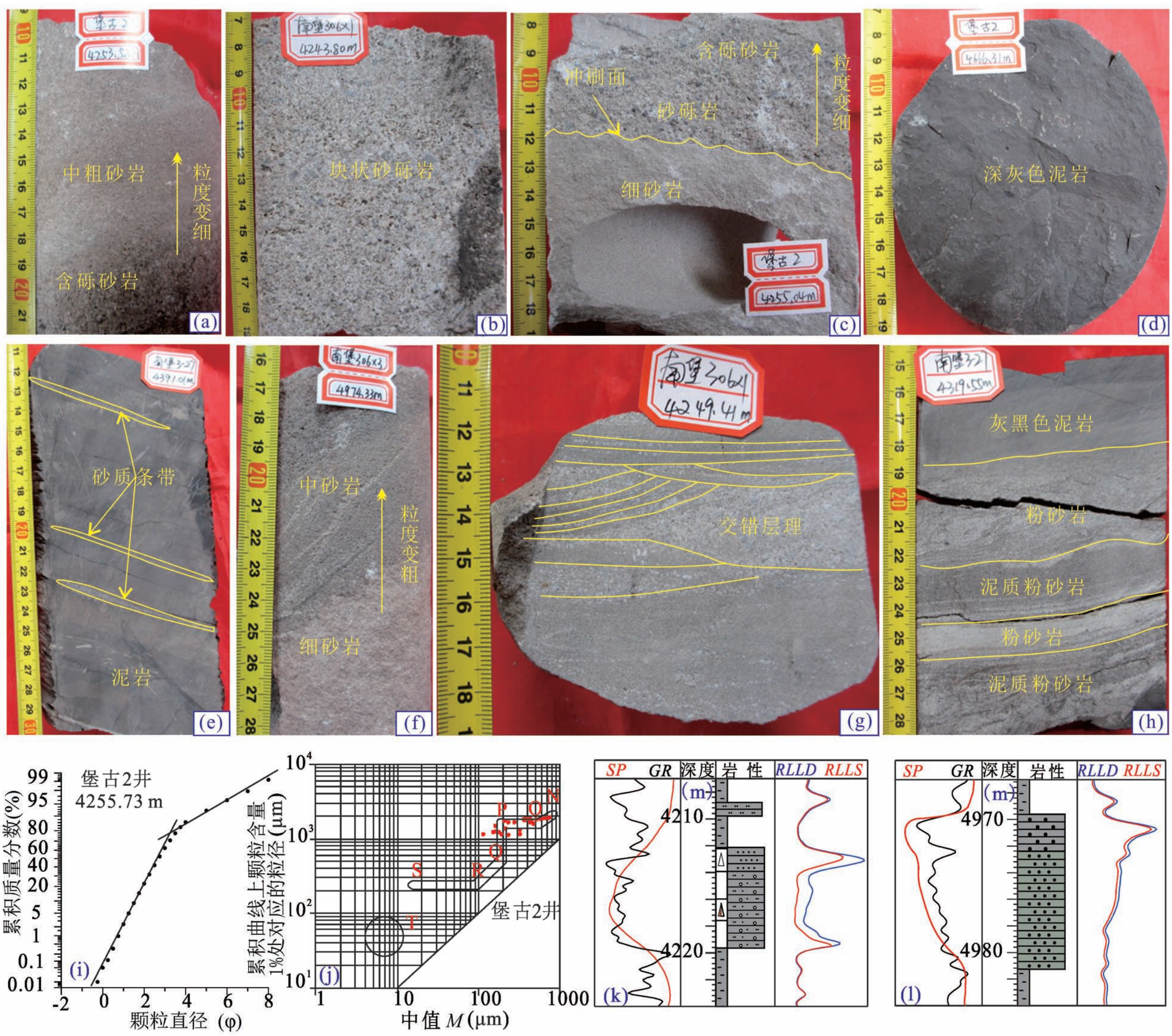

图 2 渤海湾盆地南堡凹陷南部主要沉积砂体岩芯、粒度及测井响应特征

Fig. 2 Characteristics of core, grain size and logging response by main sedimentary sand bodies in the south of Nanpu Sag, Bohai Bay Basin

(a)堡古 2 井,4253.58 m,沙一段,由下到上为含砾砂岩渐变为中粗砂岩,正粒序特征;(b)南堡 306×1 井,4243.80 m,沙一段,块状砂砾岩;(c)堡古 2 井,4255.04 m,沙一段,冲刷面,冲刷面之下为细砂岩,之上由砂砾岩向含砾砂岩渐变;(d)堡古 2 井,4666.31 m,沙一段,深灰色泥岩;(e)南堡 3-27 井,4391.01 m,沙一段,深色泥岩夹砂质条带;(f)南堡 306×3 井,4974.33 m,沙一段,由下到上为细砂岩渐变为中砂岩,反粒序特征;(g)南堡 306×1 井,4249.41 m,沙一段,槽状交错层理;(h)南堡 3-27 井,4319.55 m,沙一段,粉砂岩与泥质粉砂岩互层,顶部为灰黑色泥岩;(i)堡古 2 井,4255.73 m,沙一段粒度概率曲线图,两段式;(j)堡古 2 井 C—M 图,发育 NO—OP 段;(k)南堡 3-26 井,水下分流河道的岩—电测井响应特征;(l)南堡 306×3 井,河口坝的岩—电测井响应特征。SP—自然电位;GR—自然伽马;RLLD—深侧向电阻率;RLLS—浅侧向电阻率

(a) Pg2, 4253.58 m, Es_1, the gravel-bearing sandstone gradually changes to medium—coarse sandstone from bottom to top, Positive grain order; (b) Np306×1, 4243.80 m, Es_1, massive sandstone; (c) Pg2, 4255.04 m, Es_1, erosion surface, Below the scouring surface is fine sandstone, and above it gradually changes from conglomerate to conglomerate sandstone; (d) Pg2, 4666.31 m, Es_1, deep grey mudstone; (e) Np3-27, 4391.01 m, Es_1, sandy banding of dark mudstone; (f) Np306×3, 4974.33 m, Es_1, degradation from fine sandstone to medium sandstone from bottom to top with inverse grain order characteristics; (g) Np306×1, 4249.41 m, Es_1, trough cross stratification; (h) Np3-27, 4319.55 m, Es_1, interbedded siltstone and argillaceous siltstone with grey black mudstone at top; (i) Pg2, 4255.73 m, grain-size probability curve of Es_1, two-segment; (j) C—M diagram of Pg2, development of NO—OP segment; (k) NP3-26, Rock—electric logging response characteristics of subaqueous distributary channel; (l) Np306×3, Rock—electric logging response characteristics of estuary dam; SP — natural potential; GR — gamma ray; RLLD — deep lateral resistivity; RLLD — shallow lateral resistivity

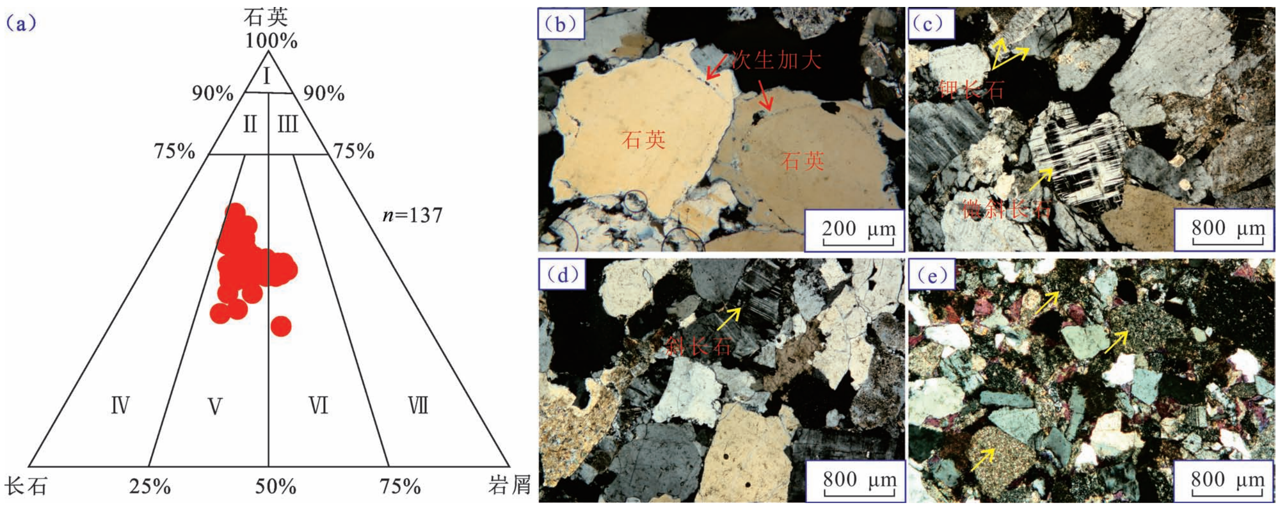

图 3 渤海湾盆地南堡凹陷南部沙一段储层岩石学特征

Fig. 3 Petrology characteristics of reservoirs of Es_1 in the south of Nanpu Sag, Bohai Bay Baisin

(a)南堡凹陷南部深层储层岩石学特征三端元图：Ⅰ—石英砂岩;Ⅱ—长石石英砂岩;Ⅲ—岩屑石英砂岩;Ⅳ—长石砂岩;Ⅴ—岩屑长石砂岩;Ⅵ—长石岩屑砂岩;Ⅶ—岩屑砂岩;(b)堡古 2 井,4254.60 m,沙一段,石英一级灰白干涉色,次生加大,正交光;(c)堡古 2 井,4252.09 m,沙一段,钾长石,卡斯巴双晶;微斜长石,格子双晶,正交光;(d)堡古 2 井,4524.02 m,沙一段,斜长石,聚片双晶,正交光;(e)堡古 2 井,4214.31 m,沙一段,岩浆岩岩屑,齿状嵌晶结构

(a) Three-terminal element diagram of petrological features of deep reservoir in the south of Nanpu Sag: Ⅰ—Quartzose sandstone; Ⅱ—Feldspathic quartz sandstone; Ⅲ—Debris-arkosic sandstone; Ⅳ—Arkose; Ⅴ—Debris-arkosic sandstone; Ⅵ—Feldspar lithic sandstone; Ⅶ—Debris sandstone; (b) Pg2, 4254.60 m, Es_1, Primary gray-white interference color of quartz, secondary enlargement, orthogonal light; (c) Pg2, 4252.09 m, Es_1, potassium feldspar, casba double crystal; Microcline, tartan twinning, orthogonal light; (d) Pg2, 4254.02 m, Es_1, plagioclase, polysynthetic twin, orthogonal light; (e) Pg2, 4214.31m, Es_1, magmatic debris, tooth-shaped poikilitic texture

该沉积砂体;河口坝砂体发育较为局限,仅在南堡 306×3 井至南堡 3-27 井井区钻遇了该砂体(图 1c)。

表 1 渤海湾盆地南堡凹陷南部沙一段不同类型储集空间面孔率统计表

Table 1 Statistical table of face rates of different types of storage spaces of Es_1 in the south of Nanpu Sag, Bohai Bay Basin

量级	原生孔隙	次生孔隙	微裂缝	总面孔率	孔径(mm)
最大值	7.0%	9.0%	—	11%	8.4
峰值	1.68%~3.36%	0.94%~3.76%	部分	3.2%~6.5%	2.2~2.9
平均值	2.5%	2.2%	—	4.7%	2.3

2.2　储层岩石学特征

通过研究区 3 口井 127 个岩芯薄片鉴定结果,根据砂岩三端元分法,南堡凹陷南部深层沙一段储层岩石类型以岩屑长石砂岩为主,其次为长石岩屑砂岩(图 3a)。石英含量 21%~50%,平均值 42.6%;长石含量 16%~33%,平均值 27.3%;岩屑含量 7%~35%,平均值 18.1%。岩屑主要为岩浆岩岩屑(3%~15%,平均值 8.9%),含沉积岩岩屑(1%~8%,平均值 4.3%)和变质岩岩屑(1%~15%,平均值 4.9%),岩浆岩岩屑占岩屑总量的 49.2%,岩浆岩岩屑类型为酸性和中性岩浆岩。岩石组分含量表明:①刚性颗粒石英含量较高,石英、长石和岩屑的比例为 2.4 ∶ 1.5 ∶ 1,具有“高石英、低岩屑”的特点,成分成熟度较高;②岩屑中刚性岩屑(岩浆岩岩屑)含量较高,岩浆岩岩屑、变质岩岩屑和沉积岩岩屑的比例接近 2 ∶ 1 ∶ 1。碎屑粒径主要在 0.35~2.0 mm,平均为 0.89 mm,磨圆为次圆状,分选较好。石英在镜下可见次生加大边(图 3b),在镜下可见钾长石(图 3c)、斜长石(图 3d)和微斜长石(图 3c)等多种类型长石,岩浆岩岩屑镜下呈齿状嵌晶结构(图 3e)。

2.3　储层物性特征

通过研究区 5 口井 126 个碎屑岩样品物性测试,统计储层孔隙度分布范围为 3.2%~15.6%,平均值 10.9%;渗透率分布范围 $1.059×10^{-3}$ $μm^2$~$121×10^{-3}$ $μm^2$,平均值 $26.36×10^{-3}$ $μm^2$,属于低孔中渗储层(图 4)。研究区孔隙度、渗透率相关性为

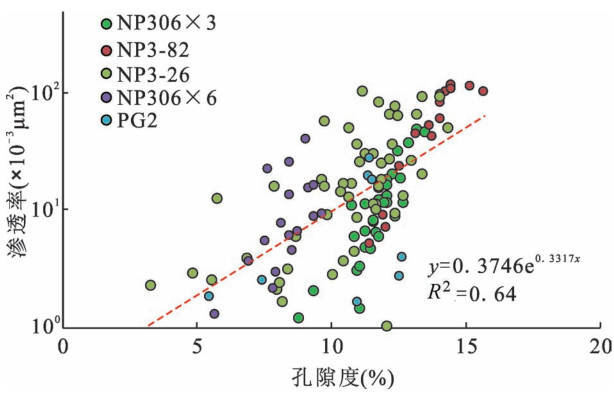

图 4 渤海湾盆地南堡凹陷南部沙一段孔隙度与渗透率关系

Fig. 4 Diagram of porosity and permeability of Es_1 in the southern Nanpu Sag, Bohai Bay Basin

0. 64,相关性较好。但也有部分样品表现出孔隙度较低、渗透率高的特征,例如南堡 306×6 井的部分样品孔隙度小于 10%,渗透率可以达到(20~40)×10^{-3} μm^2,说明该类储层虽然孔隙不大,但是喉道的连通性较好。

2.4 储集空间类型

2.4.1 孔隙类型

通过岩石薄片鉴定、铸体薄片图像和扫描电镜图像等实验分析,研究区主要发育 3 类储集空间:原生孔隙、次生孔隙和微裂缝(表 1)。原生孔隙与次生孔隙比例接近 1 : 1,微裂缝在局部样品发育。①原生孔隙:南堡凹陷南部深层的原生孔隙形状较为规则,多以三角形和多边形出现,边缘清晰(图 5a~g)。原生面孔率为微量~7.0%,平均值为 2.5%,占总面孔率的 53.2%(样品数 153)。主要为原生残余粒间孔,粒间常见黏土矿物、自生六方柱状微晶石英(图 5c)、碳酸盐矿物(图 5d)和球粒状黄铁矿微晶集合体。黏土矿物主要为丝缕状伊利石,呈孔隙充填式及衬垫式充填粒间分布在颗粒边缘或表面(图 5b~f)。原生孔隙一般分布较为均匀,单独个体较大,常与粒缘喉道构成有效的孔喉网络。②次生孔隙:研究区次生孔隙主要为粒间溶孔,其次为粒内溶孔。常呈港湾状、不规则状以及铸模孔,边缘模糊(图 5a~g),主要是由长石和易溶岩屑颗粒等组分溶蚀形成。次生面孔率为 1.0%~9.0%,平均值为 2.2%,占总面孔率的 46.8%(样品数 153)。在镜下可见长石的淋滤溶蚀(图 5e)和长石沿节理缝被溶蚀(图 5f)。次生孔隙一般为原生孔隙的扩大部分,

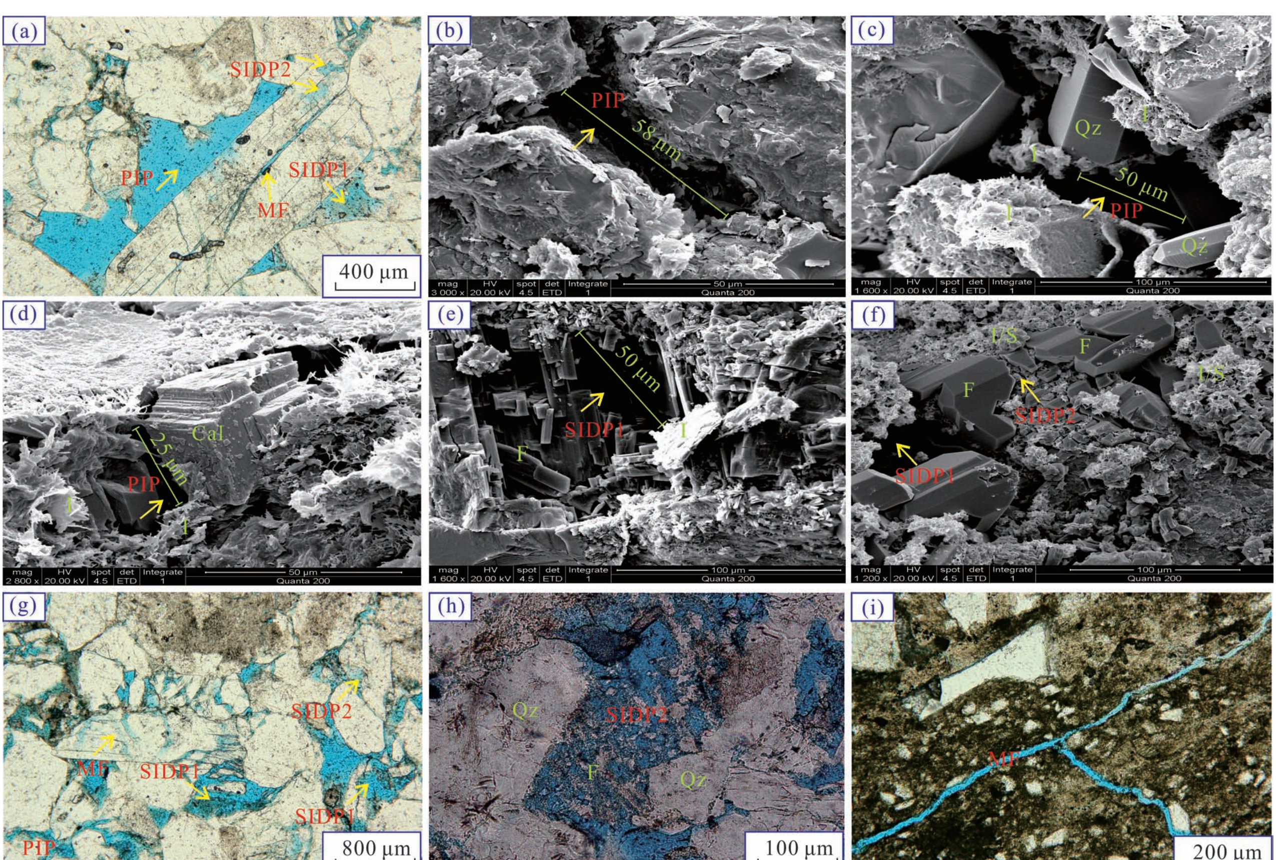

图 5 渤海湾盆地南堡凹陷南部沙一段储层储集空间类型

Fig. 5 Types of Reservoir space of Es_1 in the south of Nanpu Sag, Bohai Bay Basin

(a)堡古 2 井,4251.21 m,原生残余粒间孔,次生粒间溶孔,次生粒内溶孔,颗粒压裂缝,铸体薄片;(b)堡古 2 井,4249.66 m,原生残余粒间孔,长轴大小 58 μm 左右,粒表分布伊蒙混层及碳酸盐矿物,扫描电镜;(c)堡古 2 井,4249.29 m,原生残余粒间孔,长轴大小 50 μm 左右,粒间分布六方柱状微晶石英及伊利石,扫描电镜;(d)堡古 2 井,4254.95 m,原生残余粒间孔,短轴大小 25 μm 左右,粒间分布碳酸盐矿物及伊利石,扫描电镜;(e)堡古 2 井,4214.31 m,次生粒间溶孔,长轴大小 50 μm 左右,长石淋滤溶蚀,扫描电镜;(f)堡古 2 井,4251.21 m,次生粒间溶孔、次生粒内溶孔,长石沿解理缝溶蚀,部分被伊蒙混层黏土充填,扫描电镜;(g)堡古 2 井,4254.5 m,原生残余粒间孔、次生次生粒间溶孔,次生粒内溶孔,长石颗粒解理缝,铸体薄片;(h)南堡 3-82 井,4339.5 m,次生粒内溶孔,长石颗粒溶蚀形成铸模孔,铸体薄片;(i)堡古 2 井,4216.43 m,构造作用发生破裂而形成的微裂缝,呈直线状。PIP—原生残余粒间孔;SIDP1—次生粒间溶孔;SIDP2—次生粒内溶孔;MF—微裂缝;I—伊利石;I/S—伊蒙混层;Qz—石英;F—长石;Cal—碳酸盐矿物

(a) Pg2, 4251.21 m, primary residual intergranular pores, secondary intergranular dissolved pores, Secondary intragranular dissolved pores, fracturing fracture, casting thin section; (b) Pg2, 4249.66 m, primary residual intergranular pores, the long axis is about 58 μm in size, surface distribution of illite—montmorillonite and carbonate minerals, SEM; (c) Pg2, 4249.29 m, primary residual intergranular pores, the long axis is about 50 μm in size, intergranular distribution of hexagonal columnar microcrystalline quartz and illite, SEM; (d) Pg2, 4254.95 m, Primary residual intergranular pores, the stub axis is about 25 μm in size, intergranular distribution of carbonate minerals and illite, SEM; (e) Pg2, 4214.31 m, secondary intergranular dissolved pores, the long axis is about 50 μm in size, leaching dissolution of feldspar, SEM; (f) Pg2, 4251.21 m, secondary intergranular dissolved pores and secondary intragranular dissolved pores, feldspar dissolved along the cleavage fracture, partially filled with illite—montmorillonite clay, SEM; (g) Pg2, 4254.5 m, primary residual intergranular pores, secondary intergranular dissolved pores, secondary intragranular dissolved pores, cleavage crack of feldspar, casting thin section; (h) Np3-82, 4339.5 m, secondary intragranular dissolved pores, the feldspar particles were dissolved to form the mold hole, casting thin section; (i) Pg2, 4216.43 m, micro-fracture formed by rupture of structure are linear; PIP—primary residual intergranular pores; SIDP1—secondary intergranular dissolved pores; SIDP2—secondary intergranular dissolved pores; MF—micro-fracture; I—illite; I/S—illite—montmorillonite; Qz—quartz; F—feldspar; Cal—carbonate minerals

可以有效改善储层的孔喉结构,从而增大储层的储集能力和渗流能力。③微裂缝:研究区微裂缝主要包括受到构造作用发生破裂而形成的微裂缝、成岩过程中受到压实作用发生破裂的压裂缝以及长石颗粒的解理缝等。研究区部分微裂缝被碳酸盐、黏土等矿物充填,但仍有大部分微裂缝未被充填(图 5a、g、i),顺着微裂缝方向的溶蚀可进一步增加孔喉的连通性(图 5f),从而使得无效孔隙变成有效孔隙。

2.4.2　喉道类型

通过铸体薄片观察,南堡凹陷南部深层沙一段

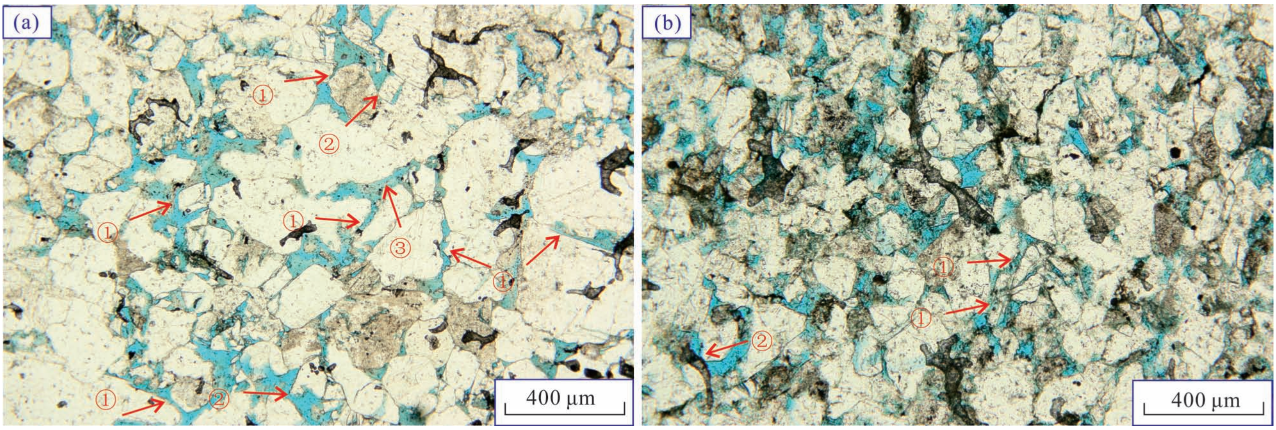

图 6 渤海湾盆地南堡凹陷南部沙一段储层喉道类型及特征差异

Fig. 6 Types and characteristics of reservoir throats of Es_1 in the south of Nanpu Sag, Bohai Bay Basin

(a)堡古 2 井,4252.50 m,59#样品:① 片状或弯片状喉道,该类喉道溶蚀特征明显,溶蚀后喉道扩大变粗,呈港湾状;② 缩颈型喉道,研究区少见;③ 孔隙缩小型喉道,研究区少见;喉道总体较粗,连通孔隙较多,孔隙连通性较好,铸体薄片;(b)堡古 2 井,4254.26 m,70#样品,喉道较细,连通孔隙较少,孔隙连通性较差,铸体薄片

(a) Pg2, 4252.50 m, sample 59#: ① Flake or curved flake throat, dissolution characteristics of this kind of throat are obvious, the throat expands and becomes thicker after dissolution, showing a harbor shape; ② Necking throat, the study area is rare; ③ Pore-reduced throat, the study area is rare, throat overall thicker, more connected pores, pore connectivity is good, casting thin section; (b) Pg2, 4254.26 m, sample 59#, fine throat, less connected pores, poor pore connectivity, casting thin section

储层喉道主要为片状或弯片状喉道，缩颈型喉道和孔隙缩小型喉道比较少见(图 6a、b)。喉道是决定储层的渗透能力的关键(王瑞飞等，2008；赵晓东等，2015)，以堡古 2 井 59#样品(4252.50 m)样品和 70#样品(4254.26 m)为例，两者岩性均为含砾砂岩，实验测得 59#样品孔隙度 12.2%，渗透率 $68.8\times10^{-3}\ \mu m^2$；70#样品孔隙度 12.7%，渗透率 $1.48\times10^{-3}\ \mu m^2$，两个样品孔隙度相似，但渗透率却具有明显的差异。通过铸体薄片图像分析(图 7a、b)，59#样品喉道平均值为 25.03 μm，连通孔隙占总孔隙 47.1%，而 70#样品喉道平均值仅有 9.16 μm，连通孔隙仅占总孔隙 19.6%，表明喉道的大小决定了连通孔隙的多少，从而决定了储层的渗透能力。两者的孔隙数目、压实过程相似，主要的区别在于 59#样品喉道受强溶蚀作用扩大变粗(图 6a)，而 70#样品溶蚀作用较弱未能有效改善孔隙的连通性(图 6b)。

3 深层优质储层成因机制

深层是否发育工业性油气流储层是深层油气勘探的主要的问题之一(贾承造等，2012；徐春春等，2017；Guo Xusheng et al., 2019；曾庆鲁等，2020)。对于碎屑岩储层，普遍认为随着埋深的增加，压实作用增强，储层物性逐渐变差，但发现在某些地质条件下，深层依然发育相对优质储层。深层优质储层成因机制较为复杂(钟大康等，2007；何生等，2009；杨华等，2017；金凤鸣等，2018；王恩泽等，2020)，主要包括沉积作用对储层物性的控制、成岩作用对储层结构的控制、古构造应力对孔隙的控制、欠压实形成的异常高压对储层的改善以及烃类的早期充注抑制储层的胶结等等。对于不同的研究区、不同的地质特点，深层优质储层的成因机制存在一定的差异。本文主要针对南堡凹陷南部深层的地质特点，基于原生孔隙的保存机制和次生孔喉的发育机制，从沉积物的粒径、岩石组分和流体通道等方面讨论研究区深层优质储层的成因机制，以期为渤海湾盆地及类似地质特点的深层油气勘探提供一定借鉴。

3.1 原生孔隙保存机制

储层抗压实能力主要包括沉积物粒径和组成沉积物的岩石组分(Wang Enze et al., 2019；王恩泽等，2020)，沙垒田凸起沉积物源为高刚性颗粒富集提供了地质条件。

3.1.1 粗岩性沉积

南堡凹陷南部深层沙一段主要的油气储集砂体是水下分流河道与河口坝砂体，在研究区河口坝砂体仅在南堡 306×3 至南堡 3-27 井井区发育，较为局限，而水下分流河道广泛分布。研究区水下分流河道的岩性主要为中粗砂岩、含砾砂岩和砂砾岩等粗岩性，粒度概率曲线图、C—M 图以及发育的多种类型交错层理，均反映了强水动力沉积环境。沉积环境不仅影响沉积类型，同时也控制沉积物粒径，影响储层物性(Dong Yuexia et al., 2010)。主要沉积砂体的物性统计结果表明(表 2)：①水下分流河道粒度最粗，粒径峰值 0.6～1.5 mm，平均粒径为 1.06 mm；孔隙度峰值 9%～15%，平均值 11.4%；渗透率峰值 $(30\sim50)\times10^{-3}\ \mu m^2$，平均值 $33.7\times10^{-3}\ \mu m^2$，在铸体薄片中可以观察到大量原生孔隙(图 2a)。②相比于水下分流河道，粒度较细的河口坝粒径峰值 0.6～1.5 mm，平均粒径 0.64 mm；孔隙度峰值 8%～12%，平均值 9.4%；渗透率峰值 $(2\sim10)\times10^{-3}\ \mu m^2$，平均值 $6.8\times10^{-3}\ \mu m^2$。③席状砂粒度最小，物性最

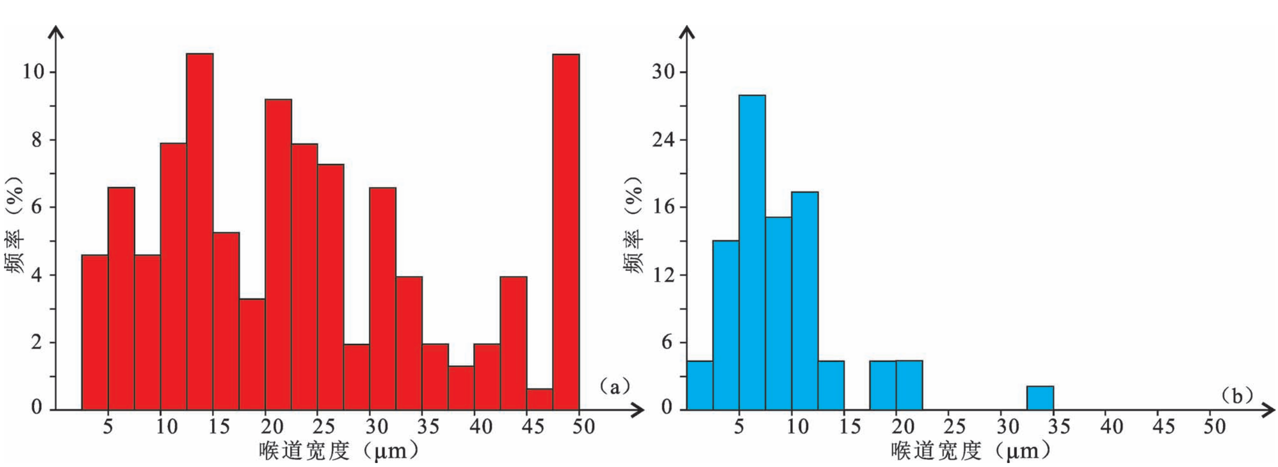

图 7 渤海湾盆地堡古 2 井 59#样品(a)样品和 70#样品(b)喉道分布直方图

Fig. 7 Histogram of throat distribution of 59 # sample (a) and 70 # sample (b) in Pg2 well, Bohai Bay Basin

表 2 渤海湾盆地南堡凹陷南部沙一段主要沉积砂体的岩性、物性统计表

Table 2 Statistics table of lithology and physical properties of main sedimentary sand bodies of Es_1 in the south of Nanpu Sag, Bohai Bay Basin

沉积砂体	岩性	粒径(mm)		孔隙度(%)		渗透率($\times10^{-3}$ μm^2)	
		平均值	峰值	平均值	峰值	平均值	峰值
水下分流河道	中粗砂岩、含砾砂岩和砂砾岩	1.06	0.6~1.5	11.4	9~15	33.7	30~50
河口坝	中砂岩、细砂岩	0.64	0.3~0.7	9.4	8~12	6.8	2~10
席状砂	粉砂岩、泥质粉砂岩	0.29	0.1~0.3	7.1	4~10	0.4	0.1~2

差，其粒径峰值 0.1～0.3 mm，平均粒径为 0.29 mm；孔隙度峰值 4%～10%，平均值 7.1%；渗透率峰值(0.1～2)×10^{-3} μm^2，平均 0.4×10^{-3} μm^2。数据显示，由于沉积环境的差异，沉积砂体的结构、物性差异明显，强水动力沉积环境中粗岩性沉积物多，粗岩性颗粒更有利于组成稳定岩石骨架，具有更强的抗压实能力，从而减少压实作用对原生孔隙的破坏，有利于原生孔隙的保存(王恩泽等，2020)。而在研究区粗岩性之所以抗压，主要是粗岩性中刚性抗压组分含量高。

3.1.2　高刚性颗粒组分

储层抗压实能力还受岩石原始组分影响，刚性颗粒含量高岩石抗压实能力强，利于原生孔隙保存(董月霞等，2014；曾庆鲁等，2020)。研究区沉积母岩为太古宇花岗岩，刚性组分石英和岩浆岩岩屑含量高。研究区刚性颗粒含量/总颗粒含量与原生孔隙面孔率/总面孔率关系表明，刚性颗粒组分与原生面孔率具有一定的正相关性(图 8)。研究区刚性颗粒含量/总颗粒含量普遍在 45%以上，当刚性颗粒含量/总颗粒含量高于 60%时，原生孔隙得到较好

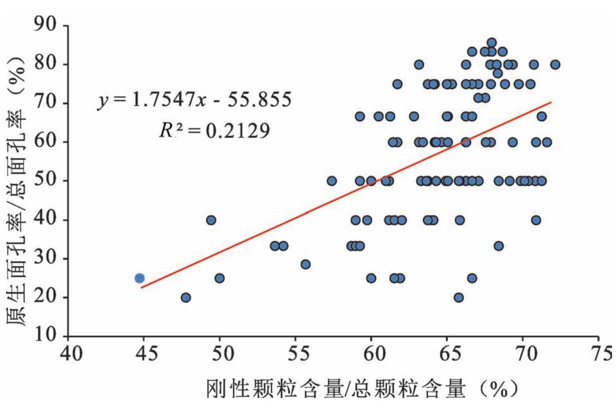

图 8 渤海湾盆地南堡凹陷南部沙一段刚性颗粒含量/总颗粒含量与原生孔隙面孔率/总面孔率关系图

Fig. 8 Diagram of the relationship between the rigid particles and the original porosity of Es_1 in the south of Nanpu Sag, Bohai Bay Basin

的保留，说明刚性颗粒的富集一定程度上抑制了储层的压实，从而保留了原生孔隙。

南堡凹陷南部深层储层经历了较强的压实作用，沉积成岩过程中，碎屑颗粒受压实作用发生颗粒重新排列(王恩泽等，2020)。研究区成岩演化主要经历了早成岩和中成岩阶段，分为中成岩 A1 和中成岩 A2 两个阶段；图 9)。早成岩阶段(距今 34～26 Ma)，储层处在浅埋藏状态，埋深小于 2 km，利用 Beard 和 Wely 公式，结合粒度分析求得的分选系数(S_0 = 1.96)计算得到研究区初始孔隙度为 32.59%，该阶段岩石处于半固结状态(图 9，A 点)，该阶段因为埋深较浅，所以压实作用相对较弱，但由于岩石比较疏松，弱压实作用仍然对岩石碎屑颗粒的排列和位移影响较大，另外，在该阶段早期碳酸盐胶结物析出，阶段末期岩石固结成型，原生孔隙明显减少(图 9，B 点)。中成岩 A1 阶段(距今 26～6 Ma)，储层埋深大于 2 km，压实作用明显变强，长石、泥屑、云母等塑性颗粒发生挤压变形，孔隙空间进一步减少，颗粒的接触关系由点接触变成点—线接触，刚性颗粒由于抗压能力强，不易发生变形，保留了部分原生残余粒间孔，另外在该阶段了发生了易溶矿物的溶蚀(图 9，C 点)。之后进入中成岩 A2 阶段(距今 6～0 Ma)，储层埋深超过 4 km，压实作用继续加强，颗粒紧密接触，塑性颗粒进一步变形，孔隙空间进一步减少，但由于刚性颗粒较多，原生孔隙减少幅度不大，部分刚性颗粒在强压实作用下发生破裂形成压裂缝，同时在该阶段发生晚期碳酸盐胶结，在一定程度上减小了原生孔隙(图 9，D 点)。研究区几乎所有的样品都经历了不同程度的胶结作用，通过视胶结率参数的计算(公式 1；宋子齐等，2006；赖锦等，2013)，南堡凹陷南部深层沙一段储层大多数样品视胶结率小于 20%，只有少数样品的视胶结率大于 40%，平均视胶结率为 12.9%，体现出弱胶结作用的特征。分析表明，压实作用是南堡凹陷南部深层沙一段储层孔隙减少的主要因素，与压实作用

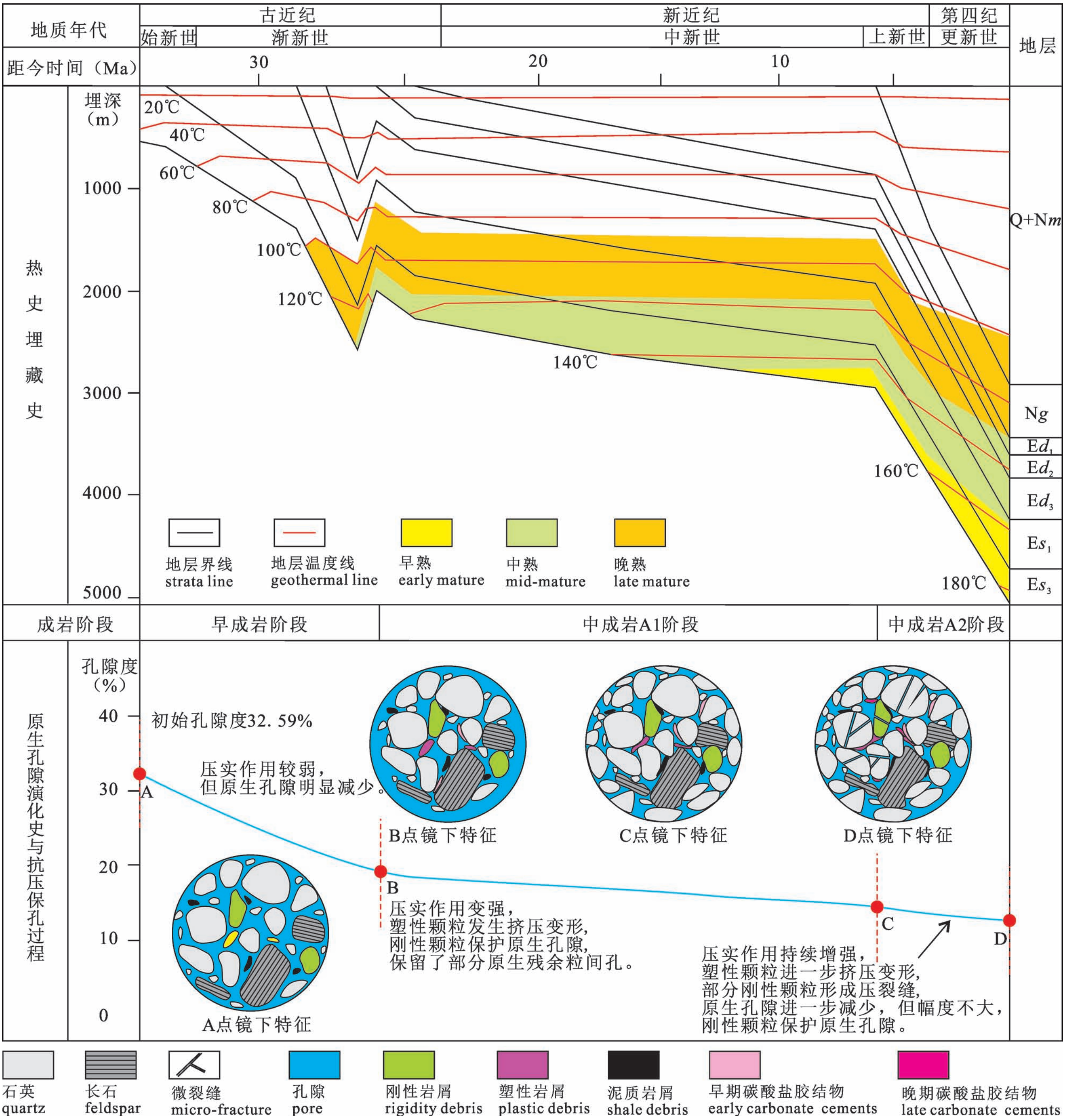

图 9 渤海湾盆地南堡凹陷南部深层刚性颗粒的抗压保原生孔过程

Fig. 9 The process of compressive preservation of pores in the deep layer of rigid particles in southern Nanpu Sag, Bohai Bay Basin

相比，胶结作用的影响并不明显。

$$视胶结率=\frac{胶结物总量}{胶结物总量+粒间孔隙体积}\times100\% \quad (1)$$

3.2 次生孔隙发育机制

3.2.1 溶蚀作用过程

南堡凹陷南部深层沙一段与东三段为不整合接触，为油气运移的主要通道（汪泽成等，2008；Guo Yingchun et al.，2013；Chen Xiangfei et al.，2016；张磊等，2018）。研究区溶蚀作用较为普遍，这主要与区域不整合以及下生上储的源储配置有关，油源断层与不整合面构成的酸性流体通道为酸性流体进入碎屑岩储层提供路径。研究区酸性流体主要包括在成岩初期的大气水的酸性流体以及烃源岩成熟之后

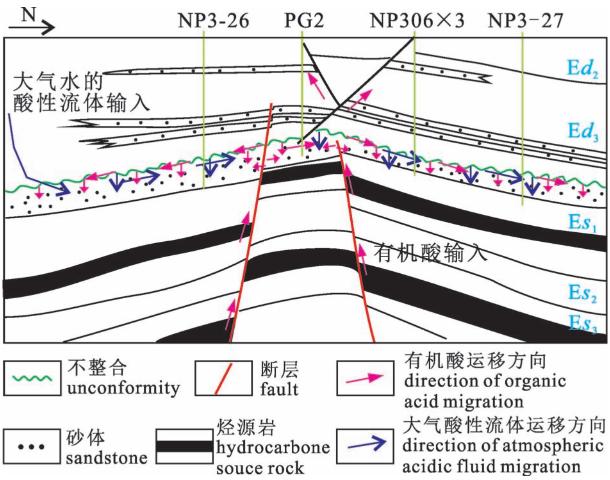

图 10 渤海湾盆地南堡凹陷南部深层南堡 3-26 井—南堡 3-27 井酸性流体输入过程示意图(剖面位置见图 1c)

Fig. 10 Schematic diagram of the acidic fluid input process in wells NP 3-26—NP 3-27 in the southern deep layer of Nanpu Sag, Bohai Bay Basin (the location of the profile is shown in Fig. 1c)

产生的有机酸,酸性流体的进入导致长石、易溶岩屑溶蚀进而形成次生孔隙(王恩泽等,2020)。在早成岩阶段研究区古沉积环境主要为湖相三角洲和湖泊相(董月霞等,2014),沉积物大都在水体之下,很少直接暴露在大气水下,所以只有少量的长石或易溶岩屑可能受大气水的淋滤溶蚀,研究区碎屑颗粒的溶蚀主要与烃源岩成熟之后产生的有机酸有关。烃源岩成熟阶段,有机酸脱羧产生 CO_2 和 H^+形成酸性流体,酸性流体顺着油源断层进入不整合面,再由不整合面区域性输入到储层中,储层中长石、易溶碎屑与酸性流体在一定温度和压力下相互反应,发生溶解(图 10)。另外,研究区碳酸盐含量较低,平均值仅有 3.13%,这主要也与溶蚀作用有关。

3.2.2　溶蚀增孔、扩喉

南堡凹陷南部深层沙一段次生孔隙主要为粒间溶孔,表明大部分易溶颗粒首先从颗粒边缘开始溶解。当酸性流体通过储集空间溶蚀矿物颗粒时,不仅增加孔隙空间,而且扩大喉道宽度。根据其成因,可以将喉道分为原生喉道和次生喉道,原生喉道一般为压实成因喉道,次生喉道为溶蚀成因喉道(刘翰林等,2017;Meng Wei et al., 2020)。原生喉道多为原生残余粒间孔经过压实作用形成,其位于矿物颗粒的交汇处,与原生孔隙连通(王伟等,2019)。次生喉道是对原生喉道进一步改造的结果,溶蚀可以新增或进一步扩大原生喉道的宽度而演变为次生喉道,从而进一步增加孔隙的连通性。在储层溶蚀前,仅发育原生喉道,原生喉道虽然较宽但连通孔隙的数目有限(图 11a);溶蚀后,一方面可以对原有部分原生喉道进行扩宽,另一方面可以增加新的次生喉道,次生喉道虽然较窄但却能与孔隙形成有效孔

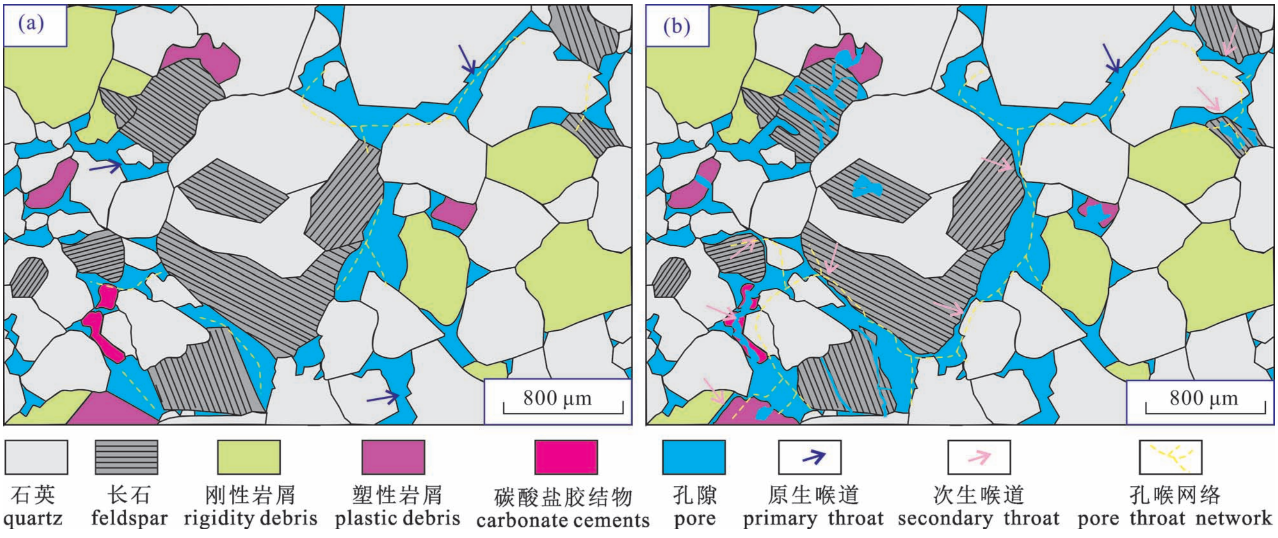

图 11 渤海湾盆地南堡凹陷南部沙一段溶蚀前后喉道与孔隙连通示意素描图(底图为堡古 2 井 4251.88 m 铸体薄片)

Fig. 11 Sketch drawing of the connection between throat and pore before and after dissolution of Es_1 in the south of Nanpu Sag, Bohai Bay Basin (the bottom diagram is 4251.88 m cast thin section of Pg2)

(a)溶蚀前,有限的孔喉连通网络;(b)溶蚀后,形成了有效的孔喉连通网络,提高了储层渗透能力

(a) limited pore throat connectivity network before dissolution; (b) after dissolution, an effective pore throat connectivity network is formed, which improves the reservoir permeability

喉网络,从而增加孔隙连通性,提高储层的渗透能力(图 11b)。以堡古 2 井 59#样品(4252.50 m)样品和 70#样品(4254.26 m)为例,次生喉道可以增加储层约 27.5%的储层连通性,但对孔隙空间的增加较为局限,这也是研究区“低孔中渗”储层形成的原因,在研究区溶蚀对于增加储层渗透能力要优于储集能力。

4 结论

(1)南堡凹陷南部深层沙一段优质碎屑岩储集砂体为中粗砂岩、含砾砂岩和砂砾岩等粗岩性砂体,为辫状河三角洲沉积,沉积母岩为南部沙垒田凸起的太古花岗岩,石英、岩浆岩岩屑等刚性组分含量高,岩石类型以岩屑长石砂岩为主。

(2)南堡凹陷南部深层沙一段优质碎屑岩储层主要发育原生孔隙、次生孔隙和微裂缝 3 类储集空间,原生孔隙与次生孔隙含量相当;喉道主要为片状或弯片状喉道;储层平均孔隙度为 10.9%,平均渗透率为 $26.36\times10^{-3}\ \mu m^2$,属于低孔中渗储层。

(3)南堡凹陷南部深层沙一段优质碎屑岩储层成因机制主要是:粗岩性沉积和高刚性岩石组分含量为储层的抗压保原生孔、微裂缝的形成提供物质基础,油源断裂、不整合面为酸性流体的进入提供路径,进一步导致溶蚀增孔、增喉扩喉。粗岩性、高刚性组分含量、油源断层与不整合面构成的酸性流体通道是该区优质储层形成的关键,为储层的抗压实作用和溶蚀作用奠定基础,溶蚀作用对孔隙空间的增加较为局限但能形成有效孔喉网络,提高储层渗透性。

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Characteristics and genetic mechanism of high-quality clastic reservoirs in the 1st Member, Paleogene Shahejie Formation in the southern Nanpu Sag, Bohai Bay Basin

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Objectives: It is generally considered that the lower limit of the effective reservoir depth of clastic reservoirs in the Nanpu Sag of the Bohai Bay Basin is 4 km. If deeper than 4 km, that the deep clastic reservoirs would be no longer have industrial oil and gas production capacity. However, the Well PG2 in the southern Nanpu Sag encountered high-quality clastic reservoirs in the 1st Member of Paleogene Shahejie Formation (Es_1) to a depth of 4.2 km and obtained a high-production oil & gas flow. In order to reveal the characteristics and genesis of this reservoirs, and reduce the exploration risk of deep oil and gas layers, we discussed its characteristics and genetic mechanism.

Methods: To investigate the characteristics and genetic mechanism of the Es_1 reservoirs, thin sections and scanning electron microscopy (SEM) images were obtained from the Petro China Jidong Oilfield Company. Reservoir physical properties, including porosity and permeability, were evaluated from 126 core samples selected from 5 boreholes; the samples were tested with a RecCore-04 Nuclear Magnetic Resonance Rock Spectrometer at room temperature (20 ℃). The grain size, diagenetic features, and porosity were evaluated from 127 samples acquired from 3 boreholes, and thin sections were analysed under a polarizing microscope to highlight the reservoir spaces; the thin sections were dyed with blue epoxy. A total of 27 samples from 1 boreholes were selected, and the samples were tested using a QUANTA 200 scanning electron microscope with an accelerating voltage of 20 kV and a current of 50~100 pA.

Results: Research shows that the type of reservoirs deeper than 4 km in south of Nanpu Sag are low porosity and medium permeability, and reservoirs space incudes primary pores, secondary pores and micro-fractures. The sedimentary period of Es_1 was in a strong hydrodynamic sedimentary environment. The braided river delta front divergent channel sand bodies were widely developed. The lithology is mainly coarse lithology such as medium—coarse sandstone, conglomerate sandstone and gravel. Rock type is mainly lithic feldspar sandstone. High content of rigid components such as quartz and magmatic rock cuttings. The reservoir still retains some of the original residual intergranular pores under strong compaction, and some rigid components form micro-fractures. There is regional unconformity contact between Es_1 and Ed_3. The organic acid produced by the acidic fluid of atmospheric

water in the early stage of diagenesis and after the source rock matures enters the reservoir through the oil source fracture and unconformity surface in the late diagenesis, resulting in feldspar and soluble debris dissolves to form secondary pores. The dissolution not only increases the pore space, but also enlarges the throat width.

Conclusions: It is concluded that coarse lithology, high content of rigid components provide the material basis for the preservation of primary pores. Oil source faults and unconformities provide pathways for the entry of acidic fluids and promote the development of secondary pores. And the dissolution effect is better than the reservoir capacity for increasing the reservoir permeability. This study provides references for the evaluation of high-quality reservoirs and benefit exploration in the Bohai Bay Basin.

Keywords: Bohai Bay Basin; the southern Nanpu Sag; the 1st Member of Shahejie Formation; high-quality clastic reservoir; reservoir characteristics; formation mechanisms

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