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柴北缘腹部深层异常高孔—渗储层成因分析

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摘 要 根据钻井岩芯及铸体薄片鉴定结果,结合扫描电镜、物性统计及测、录井资料,探讨了柴北缘腹部埋深大于3 000 m的异常高孔—渗储层的形成原因及主控因素。结果表明深部异常高孔—渗储层主要分布在古近系下干柴沟组,是一套辫状河三角洲到滨—浅湖沉积,粒度较细,以粉砂岩和细砂岩为主,岩性为长石岩屑砂岩和岩屑长石砂岩。孔隙类型以原生粒间孔为主,其次为次生溶蚀孔隙和少量裂隙,孔—喉匹配性好。深部异常高孔—渗带主要受控于沉积环境,后期成岩作用和异常高压系统也促使了优质储层的形成。古近系下干柴沟组发育的辫状河三角洲分流河道砂体和滨—浅湖砂体具有良好的成分成熟度和结构成熟度,泥质杂基含量较低,是形成优良储层的基础条件;早期碳酸盐胶结物和高含量的刚性颗粒在深埋过程中有效抵御了压实作用对孔隙的破坏;储集层上、下部发育大套厚层泥岩,在沉积成岩过程中泥岩层内流体排出受阻而滞留在孔隙空间内,孔隙流体承担了部分负荷从而削弱了正常压实作用对中间砂岩层的影响,保存了大部分原生孔隙,在柴北缘腹部深层形成了优质碎屑岩储层。

关键词 沉积环境;成岩作用;异常高压;深部储层;柴达木盆地

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0 引言

随着我国浅层油气勘探开发难度的日益加大,将勘探开发目标由浅层转向深层已经是一种必然趋势[1-2]。Schmidt *et al*.[3]研究认为,埋深超过3 000 m的储层中,原生孔隙因为强烈的压实作用、胶结作用等几乎损失殆尽,孔隙类型主要以次生孔隙为主。但最新研究成果表明[4-7],在特定的地质条件下碎屑岩储层中的原生孔隙能被有效保存到3 500~4 500 m左右,并形成优质储层。

柴达木盆地北缘构造带腹部地区是一个以侏罗系为烃源岩,古近系和新近系碎屑岩为储集层的含油气系统[8]。主要包括冷湖Ⅵ号构造,冷湖Ⅶ号构造,鄂博梁Ⅲ号构造及马海—南八仙构造带等(图1)[9-10]。继冷湖Ⅳ号和冷湖Ⅴ号构造油气勘探突破之后,马海、南八仙及鄂博梁等地也相继发现油气藏[11-14],但由于油气藏埋藏较深,储集岩成因复杂,前人对其主控因素研究较少,因此,弄清深部优质碎屑岩储层的形成机理及主控因素成为本区油气勘探的关键问题。本文以钻井岩芯及铸体薄片为基础,结合扫描电镜、镜质体反射率、储层物性、X衍射及测井等分析化验资料探讨了柴北缘腹部深层优质碎屑岩储层的物性特征及主控因素,以期为该区下一步的油气勘探提供依据。

1 深部储集岩岩石学特征

柴北缘腹部深层储集岩主要位于古近系下干柴沟组(E_3)和新近系上干柴沟组(N_1),岩石粒度较细,以细砂岩、粉砂岩和泥质粉砂岩为主。碎屑岩储层的主要成分依次为:石英、长石和岩屑,平均含量分别为:40.4%、30.6%和29%。根据赵澄林等[15]划分碎屑岩的模板,岩性主要为长石岩屑砂岩和岩屑长石砂岩,少量为长石岩屑质石英砂岩(图2)。胶结物以碳酸盐胶结物和泥质胶结物为主,含少量硅质胶结物和

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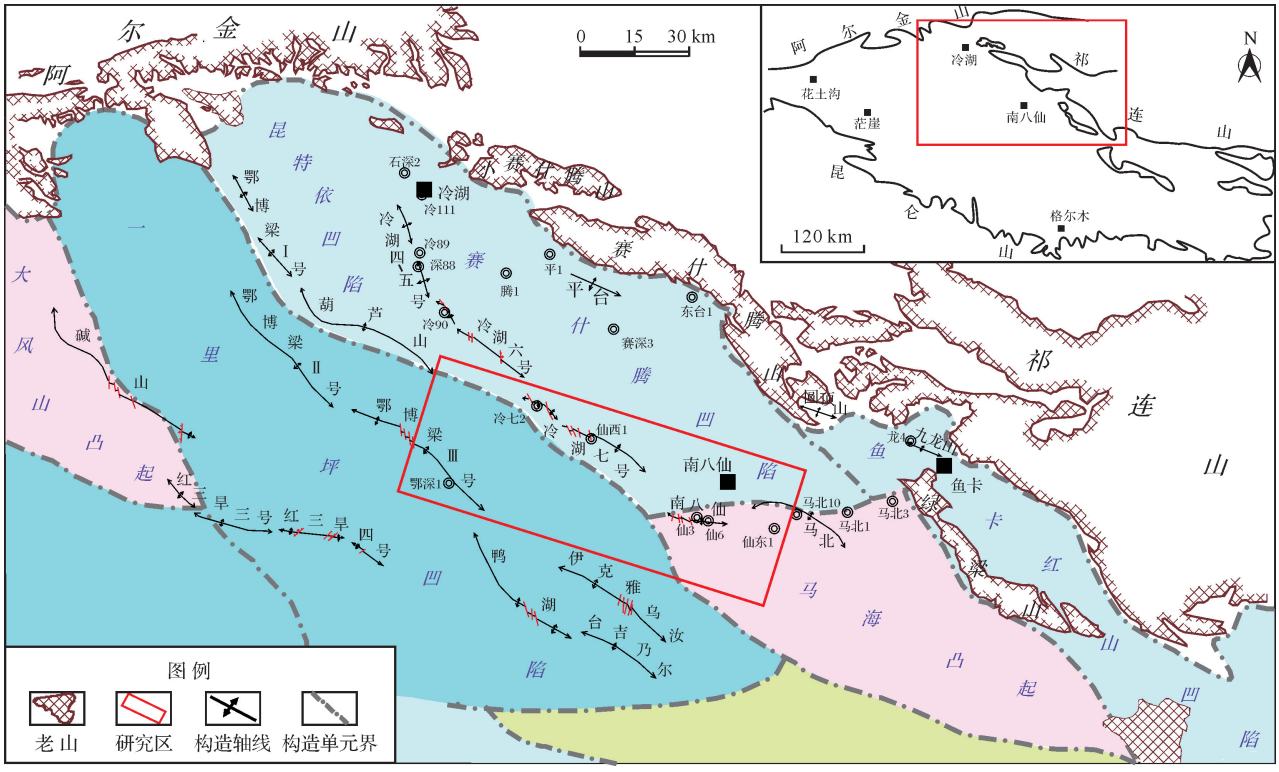

图 1 柴达木盆地北缘西段构造分区图

Fig.1 Characteristics of Structures in northwest Qaidam Basin

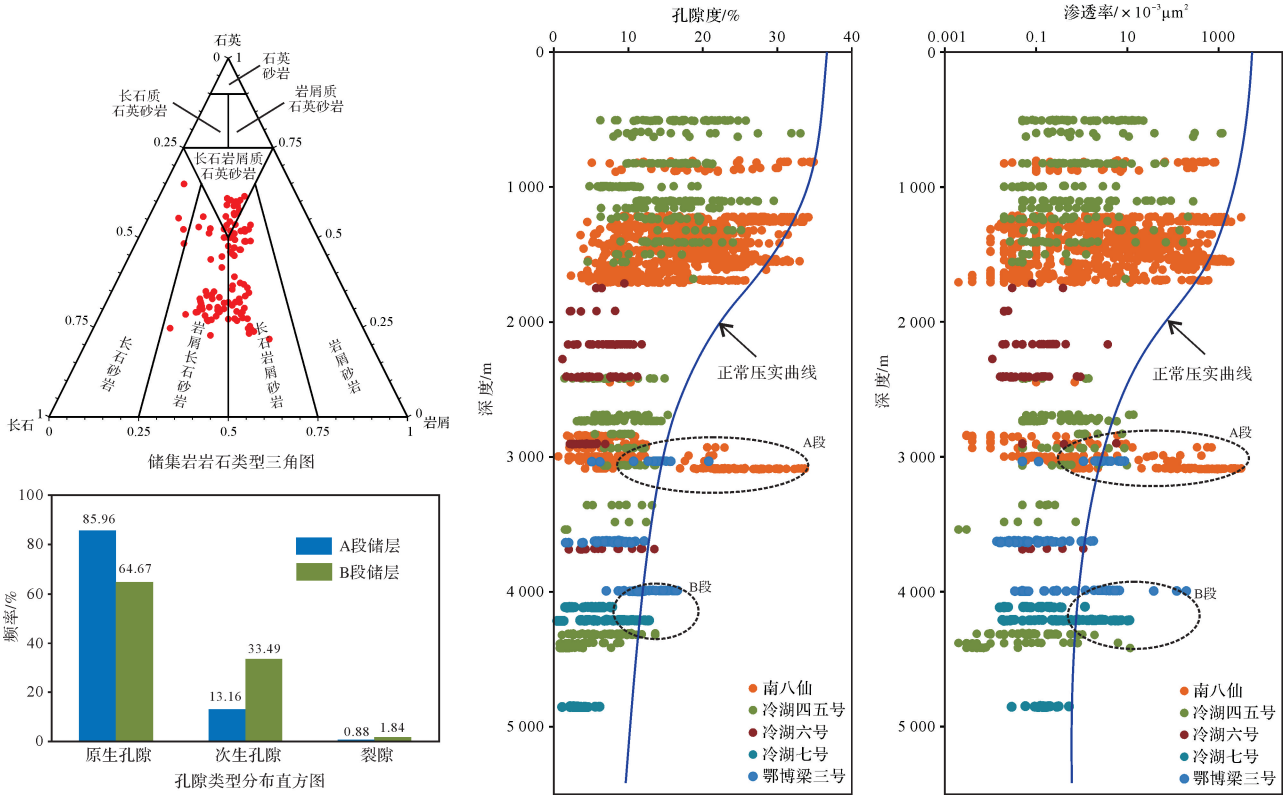

图 2 柴北缘腹部深层储集岩岩石类型及储层物性特征

Fig.2 The rock types and physical property characteristics of deeply buried reservoirs

硬石膏。镜下显示颗粒间以点—线接触为主,分选中等—较好,磨圆以次棱角—次圆状为主,具有较好的结构成熟度。

2　深部储层物性特征

2.1　物性纵向分布特征

通过 2 000 多块岩芯样品的实测数据分析发现,柴北缘腹部深部储层孔隙度及渗透率整体上具有随埋深加大而逐渐减小的趋势(图 2)。但是,变化趋势又可以划分为两个阶段:第一阶段在 0~2 000 m,孔隙度和渗透率随深度急剧减小;第二阶段为2 000 m 以后,孔隙度和渗透率的衰减速率较为缓慢。前人研究认为[16],把未受异常超压影响且溶蚀孔发育较弱的储层的最大孔隙作为正常压实孔隙,并以此绘制出孔隙度与渗透率的正常压实趋势,而高于正常压实孔隙的孔隙带被定义为异常孔—渗带。柴北缘腹部深部储层中存在两个异常高孔—渗带(图 2):A 段位于 2 900~3 100 m,B 段位于 4 000~4 200 m。A 段的物性条件明显优于 B 段,其平均孔隙度可达25.3%,平均渗透率为 826.36×10^{-3} μm^2;而 B 段的平均孔隙度为 9.8%,平均渗透率为 4.81×10^{-3} μm^2。

2.2　储层孔隙类型

根据岩芯样品铸体薄片及扫描电镜分析,发现深部储层主要发育原生孔隙,以压实—胶结剩余粒间孔为主;其次为次生孔隙,以粒间溶蚀孔和粒内溶蚀孔为主;另外还发育少量压裂缝。根据储集空间类型的不同可将异常高孔—渗带分为原生孔隙型和原生+次生孔隙型两种类型。异常高孔—渗带 A 段储层中原生孔隙占 86.0%,次生孔隙占 13.2%,裂隙占 0.8%(图2、图3a),属于典型的高原生孔隙异常高孔—渗

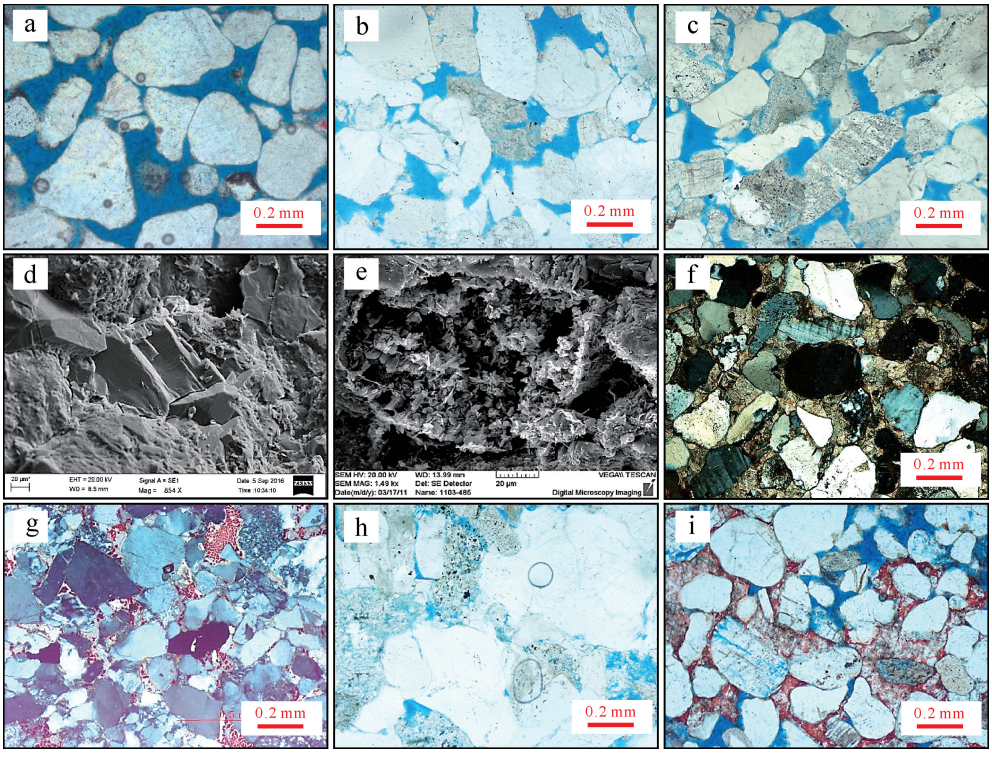

图 3　柴北缘腹部深层储集岩成岩作用特征

a.仙东 1 井,3 087.06 m,E_3^1,中—细粒岩屑长石砂岩,分选中等,次圆状,颗粒间以点接触为主,粒间孔发育,少量粒内溶孔,孔隙连通性好(-)×100;b.仙西 1 井,4 211.72 m,E_3^2,中—粗粒长石岩屑砂岩,分选中等—差,次棱角状,颗粒间以点—线接触为主,粒间孔发育,其次为粒间溶孔和粒内溶孔,孔隙连通性好(-)×100; c.仙西 1 井,4 210.77 m,E_3^2,中—粗粒岩屑长石砂岩,分选中等,次棱角状,颗粒间以点接触为主,粒间孔发育,其次为粒间溶孔和粒内溶孔(-)×100;d.仙西 1 井,4 111.84 m,E_3^2,细砂岩,方解石充填裂隙,可见微裂隙;e.鄂深 1 井,3 989.74 m,N_1,粉砂岩,颗粒内溶孔中发育针叶状绿泥石及丝状伊利石;f.仙西 1 井,4 853.83 m,E_3^2,中—细粒岩屑长石砂岩,泥晶方解石呈基底式胶结,无可见孔(+)×100;g.冷七 2 井,5 276.00 m,E_3^2,中—细粒岩屑长石砂岩,呈连生式充填,孔隙式胶结的含铁方解石,无可见孔(+)×100;h.仙西 1 井,4 212.57 m,E_3^2,中—粗粒长石岩屑砂岩,粒间杂基溶蚀形成粒间溶孔,部分颗粒被溶蚀形成粒内溶孔 (-)×100;i.仙东 1 井,3 084.44 m,E_3^1,中—细粒岩屑长石砂岩,颗粒溶蚀形成粒内溶孔,孔隙连通性好(-)×100

Fig.3　The diagenesis characteristics of deeply buried reservoirs

带;异常高孔—渗带 B 段储层中原生孔隙占 65.5%,次生孔隙占 32.5%,以及少量混合扩大孔,压裂隙占 2%(图 2、图 3b~e),此异常高孔带属于高原生+次生孔隙型异常高孔—渗带。

3 异常高孔—渗带控制因素

储层物性的控制因素主要包括沉积环境和成岩作用两个方面[17-19]。对于储层而言,即使在同一物源,相同的沉积环境内不同的砂体类型也会产生储集性能的差异[20]。成岩过程中埋深速率及外部的温压环境也会对储集性能产生较大的影响[6]。

3.1 沉积环境

柴北缘腹部深层储集岩主要发育在辫状河三角洲—滨浅湖沉积体系中[21],粒度较细。通过岩芯样品实测孔隙度和渗透率的分析(图 4),结果显示孔隙度集中分布在 4%~16%,渗透率分布在(0.01~10 000)×10^{-3} μm^2之间,在对数坐标中孔隙度和渗透率具有较好的正相关关系。说明孔隙类型主要是原生粒间孔隙,渗透率的高低受控于孔隙度发育程度[22-23],渗滤通道主要是与孔隙有关的粒间孔隙而非粒内溶孔或裂缝等其他通道,属于孔隙型储层[24-25],物性条件受沉积环境的影响较大。辫状河三角洲前缘水下分流河道砂体具有较强的水动力条件,泥质杂基含量少,分选和磨圆较好,是典型的以原生孔隙为主的储层,孔—渗相关性也最好;辫状河三角洲平原分流河道砂体孔—渗相关性较好,但物性条件差异较大;滨—浅湖砂体粒度较细,孔—渗相关性中等。这说明柴北缘地区深部储层受沉积环境的影响明显,沉积环境是形成深部优质碎屑岩储层的基础条件。

3.2 成岩作用

3.2.1 压实作用

前人研究认为[26],碎屑岩中的碎屑成分和粒度特征对物性影响最大。石英、长石及刚性岩屑(花岗岩、石英岩等)含量越高,其抵御压实作用的能力就越强。统计发现深部异常高孔—渗带石英+长石+刚性岩屑的含量超过了 71%,有效抵御了压实作用对物性的破坏。利用 Housekencht[27] 的判别方法,定量评价异常高孔—渗带内的压实与胶结作用对孔隙度的影响(图 5a),结果显示异常高孔—渗带 A 段样品压实作用平均仅减少 25%的原始空隙,样品保留了大量的原始孔隙,孔隙度在 20%~32%之间,孔隙连通性好。B 段样品由于埋藏较深,经历了缓慢压实作用的影响,压实作用平均减少了 60%左右的原始孔隙,压实减孔作用明显。因此,对于深部储层来说压实作用具有明显的分异性,A 段受压实作用影响较小,而 B 段的压实减孔作用较为明显,损耗了大量的原始孔隙。

3.2.2 胶结作用

柴北缘腹部深层储集岩中胶结物以碳酸盐胶结物为主,硫酸盐胶结物仅在局部地区发育,另外还发育少量的黄铁矿和硅质胶结物。碳酸盐胶结物可分为早、晚两期,早期碳酸盐胶结物主要为泥微晶、连晶方解石(图3f),形成于同生—早成岩阶段,呈基底式

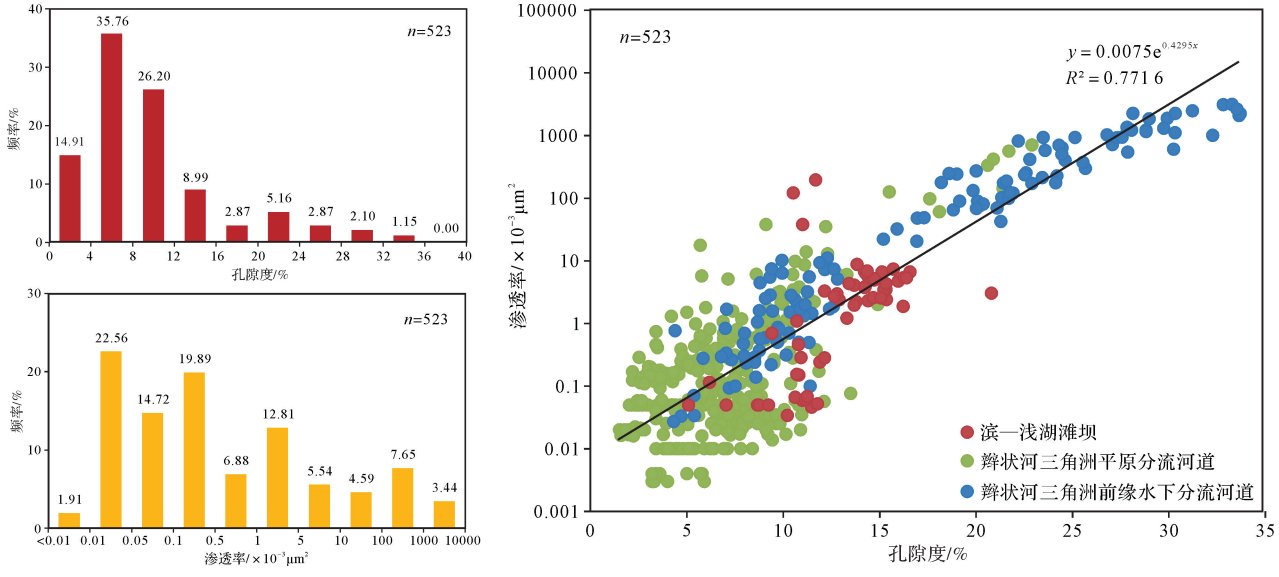

图 4 柴北缘腹部深层物性直方图及孔隙度—渗透率相关图

Fig.4 Histogram and relevance graph of porosity and permeability in deeply buried reservoirs

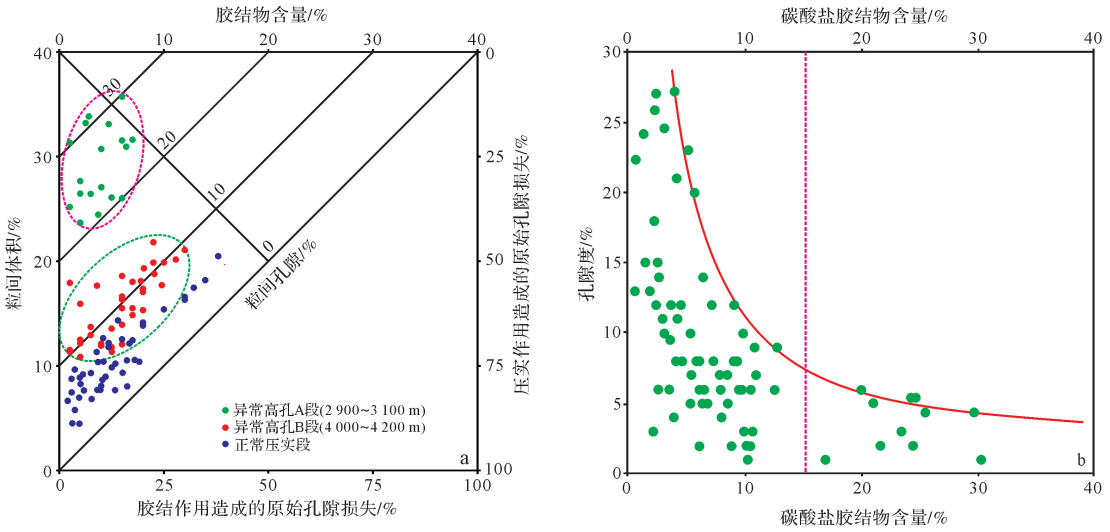

图 5　柴北缘深部储层中成岩作用与孔隙度关系

Fig.5　Influences on porosity in deeply buried reservoirs from diagenesis

胶结,与矿物颗粒接触面平直;晚期碳酸盐胶结物以含铁方解石为主,染色后呈紫红色,往往呈孔隙式胶结,或者交代早期方解石胶结物与其他碎屑颗粒,充填孔隙(图 3g)。异常高孔—渗带主要发育早期碳酸盐岩胶结物,早期胶结物对储层的影响具有双面性[28-29],一方面是抗压实作用,且为后期溶蚀作用提供了物质基础;另一方面,如果早期胶结物含量过高,完全堵塞孔隙(图 3f),会导致后期酸性流体没有活动空间[21],不利于形成次生孔隙。而柴北缘腹部深层异常高孔渗带的早期碳酸盐胶结物含量大都不超过 15%,有利于形成高孔—高渗的优质储层(图 5b)。因此,早期胶结物较为发育(<15%)也是形成优质碎屑岩储层的主要因素之一。

3.2.3　溶蚀作用

一般情况下,溶蚀作用是深部储层物性改善的重要因素,碎屑颗粒、胶结物和杂基等组分特征,以及颗粒裂纹和成岩缝都是影响形成次生溶蚀孔隙的关键因素[30-31]。通过分析柴北缘腹部深层异常孔隙带储层的溶蚀作用发现:A 段储集岩溶蚀作用较弱,次生溶蚀孔隙不发育,仅占 13.16%(图 3a,i);B 段储集岩溶蚀作用较为明显,碎屑组分和胶结物都发生了不同程度的溶蚀,并形成了一定量的粒间溶孔和粒内溶孔,次生孔隙占 32.5%(图 3b,c,h),有效的改善了储层的物性条件。

3.3　异常高压

柴北缘腹部在埋深 3 000 m 和 4 100 m 左右形成两段优质碎屑岩储层,A 段以压实和溶蚀作用较弱,胶结物少,原生孔隙非常发育,孔隙连通性好为特征;B 段以压实和溶蚀作用较强,胶结物少,原生孔隙为主,次生孔隙为辅,孔隙连通性较好为特征。前人通过对深部碎屑岩储层的主控因素研究认为[32-34],成岩作用后期的溶蚀作用形成的次生孔隙是储集性能改善的主要因素。但对于柴北缘腹部深层储层的异常高孔—渗带(A 段和 B 段储层)来讲,主要的储集空间是以原生孔隙为主,并非后期溶蚀作用改善储集性能的结果。通过综合分析,认为柴北缘腹部异常高孔—渗带(A 段和 B 段储层)是由于砂岩储层的欠压实作用形成的,这类欠压实砂岩储层发育于厚层欠压实泥岩带中。

欠压实现象是由于在泥岩被压实过程中,岩体中孔隙流体排出受阻而滞留在孔隙空间,孔隙流体承担了部分负荷而消弱了正常压实作用对储层的影响,保存了大部分原生孔隙,从而在相应砂岩层段出现异常高孔隙带[35-36]。柴北缘腹部地区古近系—新近系异常高压明显,压力系数基本在 1.7~2.0 之间,最高达 2.16;剩余压力大都在 21~24 MPa 之间,个别可达 37 MPa[37-39]。正是异常高压系统的存在,才使得大量原生孔隙得以保存[40-42]。研究表明,欠压实带具有较低的密度,在测井曲线中表现为高声波时差的特征[43-44]。前人已经对南八仙构造带的异常高压做了相关研究,认为南八仙构造带有两套压力体系,浅层的正常温压体系和深层异常高压体系,且异常高压来源于伊北凹陷巨厚层浅湖相泥岩的迅速埋深[39]。柴北缘腹部南八仙的仙东 1 井,仙 6 井,仙 3 井,冷湖七

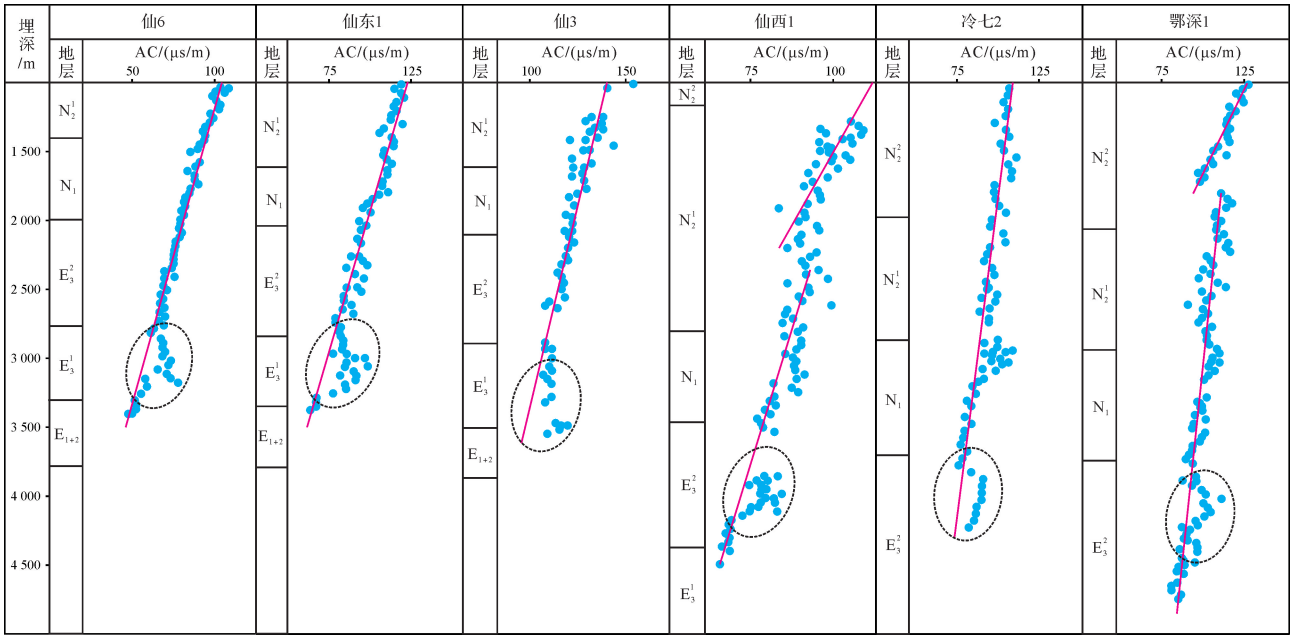

图 6 柴北缘腹部声波时差与深度的关系

Fig.6 Cross plots of depth and interval transit time of wells

号的仙西 1 井和冷七 1 井,鄂博梁三号的鄂深 1 井等多口探井中声波时差数据出现异常段(图 6),表明异常超压在柴北缘腹部是一个普遍现象,是形成深层优质碎屑岩储层的关键因素之一。

4 优质储层分布规律

柴北缘腹部下干柴沟组(E_3)主要发育辫状河三角洲—滨浅湖沉积,其中仙东 1 井下干柴沟组下段(E_3^1)的优质储层主要发育在分流河道沉积微相内,上部发育厚层泥岩段。根据图 6 中声波时差反应特征,该段正好位于欠压实泥岩段内,受欠压实泥岩的保护,大量的原始孔隙得以保存,形成优质碎屑岩储层(图 3a,i)。同样,仙西 1 井下干柴沟组上段(E_3^2)中发现的有效储层埋深在 4 110~4 236 m 之间的水下分流河道沉积微相内,岩芯样品的面孔率接近 12%(图 3b,c),和图 6 中声波时差反应的欠压实泥岩段相吻合。这都证实了在柴北缘腹部地区部深层优质碎屑岩的形成与欠压实泥岩的发育密切相关。

欠压实泥岩主要分布于古近系下干柴沟组中,主要是因为下干柴沟组广泛发育辫状河三角洲和滨—浅湖沉积,细粒沉积物发育,泥地比均大于 2/3,多为 3/4~4/5。欠压实砂岩储层多位于厚层泥岩段中,受到欠压实泥岩段的保护而形成高孔—渗储层(图 7)。而路乐河组多发育砂、泥岩互层,多为厚层砂岩夹薄层泥岩段组成,泥地比小于 1/2。这种组合不利于高压系统的形成,导致砂岩随埋深发生强烈压实,原生孔隙消耗殆尽。

5 结论

(1) 柴北缘腹部深层发育的优质碎屑岩储层粒度较细,在粉砂—细砂之间,岩性为长石岩屑砂岩和岩屑长石砂岩,泥质杂基含量较低,成分成熟度和结构成熟度较高。根据孔隙类型可将储层类型划分为原生孔隙型和原生孔隙+次生孔隙型两种类型。

(2) 深部储层物性主要受控于沉积相、成岩作用以及异常高压等因素。辫状河三角洲分流河道砂具有良好的成分成熟度和结构成熟度,泥质含量低,是形成优良储层的基础条件;异常高压带的存在对原生孔隙起到了很好的保护作用,使得原生孔隙得以较好的保存下来,有利于形成优质储层。

(3) 柴北缘腹部深层优质碎屑岩储层具有明显的欠压实特征,属于欠压实砂岩储层。欠压实砂岩储层的分布具有明显的规律性,即主要分布于古近系下干柴沟组上段和下干柴沟组下段辫状河三角洲分流河道沉积相带,发育于大套泥质岩层段内,具有较高的泥地比值,砂岩储层整体较薄,分布不均。

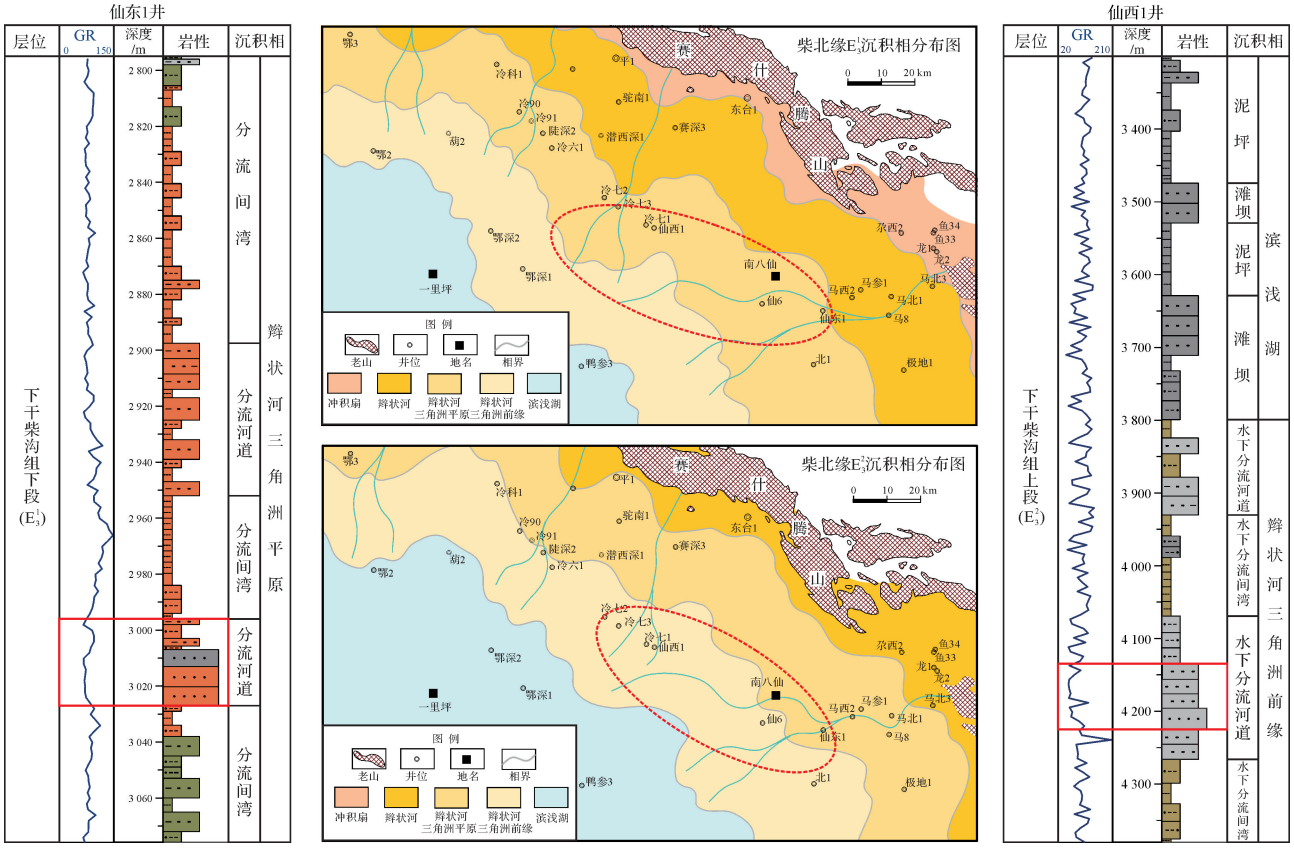

图 7　柴北缘腹部深层优质储层分布规律

Fig.7　The distribution patterns of high quality reservoirs

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Genetic Analysis of Anomalously High Porosity Zones in Deeply Buried Reservoirs in the West Part of Northern Edge of Qaidam Basin, NW China

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Abstract: According to drilling data, core samples and casting thin-sections, and combined with data from scanning electron microscopy, X-diffraction, physical property statistics and well logging, the physical properties and main controlling factors are discussed in this paper for the anomalously high porosity zones in the deeply buried reservoirs in west part of northern edge of the Qiadam Basin, northwetern China. The reservoirs buried over 3 000 m in the study area were mainly formed in the Paleogene, and there were a suite of detrital deposits of braided river delta-shallow shore. The grain sizes are small, mainly in a range of silt-fine sand. The lithologies are mainly feldspar lithic sandstone and lithic feldspathic sandstone. The pore types are dominated by intergranular pore, followed by secondary pore, and a few cracks. The pores and throat paths are well matched. The sandstone formed in the distributary channel of braided river delta front and shore-shallow lake have less argillaceous matrix with better compositional and structural maturity, which are the fundamental conditions for the high quality reservoirs formation. The carbonate cements formed in the early digenetic stage play a supporting role among particles, which effectively resist to the compaction. The thick layers of under-compacted mudstone on and below the reservoirs are key factors for the preservation of primary pores, the discharge of fluids in the pore was hampered. So the fluids bear parts of the loads and lead to the preservation of the pores.

Key words: sedimentary environment; pore type; diagenesis; abnormal high pressure; deeply buried reservoir; Qaidam Basin