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川东北元坝地区须家河组储层特征与超致密成因探讨

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内容提要：元坝地区须家河组砂岩的致密化程度极高，以超低孔、超低渗储层为主，属于超致密砂岩。本文基于铸体薄片、阴极发光、扫描电镜和物性等资料，在对砂岩的岩石组分、孔隙类型及物性特征分析的基础上，通过与国内外典型致密砂岩对比，揭示研究区砂岩较其他砂岩致密化程度高的原因，分析超致密砂岩的勘探潜能。结果表明，研究区砂岩具有较高的塑性岩屑、碳酸盐岩岩屑和黏土杂基含量；填隙物以黏土杂基和钙质胶结物为主，较强的硅质胶结作用仅发育于石英砂岩中。孔隙多为黏土杂基晶间微孔，喉道呈窄缝状或不发育，孔喉分选差，偏细歪度。砂岩致密化程度高主要有两方面的原因：一是原始组构差，成分成熟度低，含有较高的塑性岩屑、碳酸盐岩岩屑和黏土杂基含量，导致砂岩在早成岩阶段既已经历了很强的压实作用和钙质胶结作用，致密化时间早，溶蚀作用不发育；二是成岩演化阶段高，砂岩经历了中成岩阶段的压溶及进一步的钙质/硅质胶结，使得砂岩超致密化。与国内外典型致密砂岩气藏对比表明，超致密砂岩有效孔隙少，对天然气的富集能力有限。元坝地区须家河组只有孔隙度近于8%(如长石岩屑砂岩)的砂岩才可成为有利的致密气储层。

关键词：岩石组分；孔隙结构；储集物性；须家河组；元坝地区

据美国能源部对砂岩气藏的划分标准(DOE，1973)，现今已发现的大部分致密砂岩气藏都属于标准致密砂岩气藏(原地渗透率，$0.05\times10^{-3}\mu m^2<K<0.1\times10^{-3}\mu m^2$)或极致密砂岩气藏($0.001\times10^{-3}\mu m^2<K<0.05\times10^{-3}\mu m^2$)，而对于超致密砂岩气藏($0.0001\times10^{-3}\mu m^2<K<0.001\times10^{-3}\mu m^2$)的勘探较少。例如，美国落基山地区已发现的致密砂岩储层的原地渗透率主要分布在 $0.003\times10^{-3}\sim0.05\times10^{-3}\mu m^2$(美国联邦能源管理委员会 FERC，2010)，属于极致密砂岩；加拿大 Alberta 盆地 Elmworth 气田的原地渗透率分布在 $0.001\times10^{-3}\sim0.1\times10^{-3}\mu m^2$ 之间(Cant et al.，1984；Hietala et al.，1984)，属于标准致密—极致密砂岩气藏。然而，川东北须家河组砂岩的空气渗透率普遍在 $0.01\times10^{-3}\sim0.1\times10^{-3}\mu m^2$ 之间，原地渗透率为 $0.0001\times10^{-3}\sim0.001\times10^{-3}\mu m^2$，属于超致密砂岩，是致密砂岩气少有的勘探领域。

标准致密砂岩气和极致密砂岩气的勘探已在国内、外获得良好的成果。2008 年美国致密砂岩气年产量达 $1757\times10^8 m^3$(美国能源信息管理局 EIA，2008)，国内鄂尔多斯盆地上古生界也已发现了苏里格、乌审旗、榆林等多个探明储量达千亿立方米的大气田(Zhang Shuichang et al.，2008)，但超致密砂岩气的成功勘探经验较少。从四川盆地须家河组超致密砂岩的产能情况来看，虽然钻遇多口高产气井，但稳产井较少。前人勘探经验认为，有效孔隙的发育是致密砂岩气稳产的关键(Shanley et al.，2004；Cai Xiyuan，2010；Guo Tonglou，2013)，但超致密砂岩的孔隙度普遍低于5%，砂岩致密化程度高，导致油气富集区难寻。因此，明确砂岩致密化程度高的原因是研究区亟待解决的关键地质问题。本文选取国、内外六个典型致密砂岩气田与研究区进行对比，揭示研究区砂岩比其他砂岩致密化程度高的原因，并分析和探讨超致密砂岩的勘探潜能。

1　地质背景

元坝地区位于四川盆地东北部，北邻米仓山-大巴山前陆冲断带，西为龙门山前陆冲断带。燕山期以来，研究区由于受到龙门山和米仓山北西一南东

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向挤压(Luo Liang et al., 2015; Zou Yutao et al., 2015; Huang Guangming et al., 2016),形成五个次级构造单元,分别为:九龙山背斜构造带、池溪凹陷、通南巴背斜构造带、通江凹陷和苍溪-巴中低缓构造带(Guo Tonglou, 2013;图 1)。须家河组为陆相沉积,发育扇三角洲相、辫状河三角洲相和湖泊相(Zhu Rukai et al., 2009)。元坝地区须家河组厚数百米至近千米,自下而上划分为须一段至须五段五个岩性段,其中须一段、须三段、须五段以泥岩为主,须二段和须四段以砂岩为主,各段均含有不等厚的砂岩层和泥岩层,形成源、储互层的"三明治"式结构(Zhang Jian et al., 2006; Lai et al., 2016),平面上呈现出由北西向南东减薄的趋势。元坝地区须家河组的主要勘探层位除了须二段、须四段两个主要砂岩层位以外,还包括须三段源内致密砂岩层。前人对元坝地区埋藏史和热史研究认为,研究区地层在白垩纪末期达到最大埋深,深度在 5800~6300m,镜质组反射率达 1.8%~2.2%,地温高达 180~220℃(Li Jun et al., 2012; Zhang Junwu et al., 2015)。

2 储层特征

2.1 岩石学特征

2.1.1 岩石组分

元坝地区须家河组砂岩以细—中粒为主,结构成熟度中等,分选中等,磨圆度为次棱—次圆;成分成熟度较低,岩屑含量较高,平均骨架颗粒组分为 $Q_{57.4}F_{5.7}R_{36.9}$。岩性以岩屑砂岩为主,含有少量长石岩屑砂岩、岩屑石英砂岩和石英砂岩(图 2a)。此外,部分岩屑砂岩中含有较高含量的盆外碳酸盐岩岩屑,当含量超过全部岩石体积的 50%时,细分为钙屑砂岩(Folk, 1974)(后文中岩屑砂岩指一般类型岩屑砂岩,钙屑砂岩指碳酸盐岩岩屑含量超过 50%的岩屑砂岩)。

研究区砂岩中岩屑含量高,最高可达 81%,通常在 10%~50%之间,平均值为 30%。岩屑类型丰富,以沉积岩岩屑和变质岩岩屑为主,火山岩岩屑较少。变质岩岩屑有石英岩、千枚岩和片岩,沉积岩岩屑有泥岩、粉砂岩、硅质岩和碳酸盐岩岩屑。根据对成岩作用和孔隙演化的影响,可将岩屑类型划分为三类:碳酸盐岩岩屑,塑性岩屑和脆性岩屑。从岩屑类型三角图可以看出(图 2b),塑性岩屑和碳酸盐岩岩屑在须家河组砂岩中普遍发育,且部分砂岩中含有较高含量的塑性岩屑和碳酸盐岩岩屑。

各类砂岩的岩屑类型具有明显的差异性,其中,岩屑砂岩和长石岩屑砂岩中普遍发育塑性岩屑和碳酸盐岩岩屑。岩屑砂岩中塑性岩屑含量平均值为 11.8%,钙屑含量平均值为 6%;长石岩屑砂岩中塑性岩屑含量平均值为 12.3%,碳酸盐岩岩屑含量平均值为 3.9%。岩屑石英砂岩中主要发育塑性岩屑

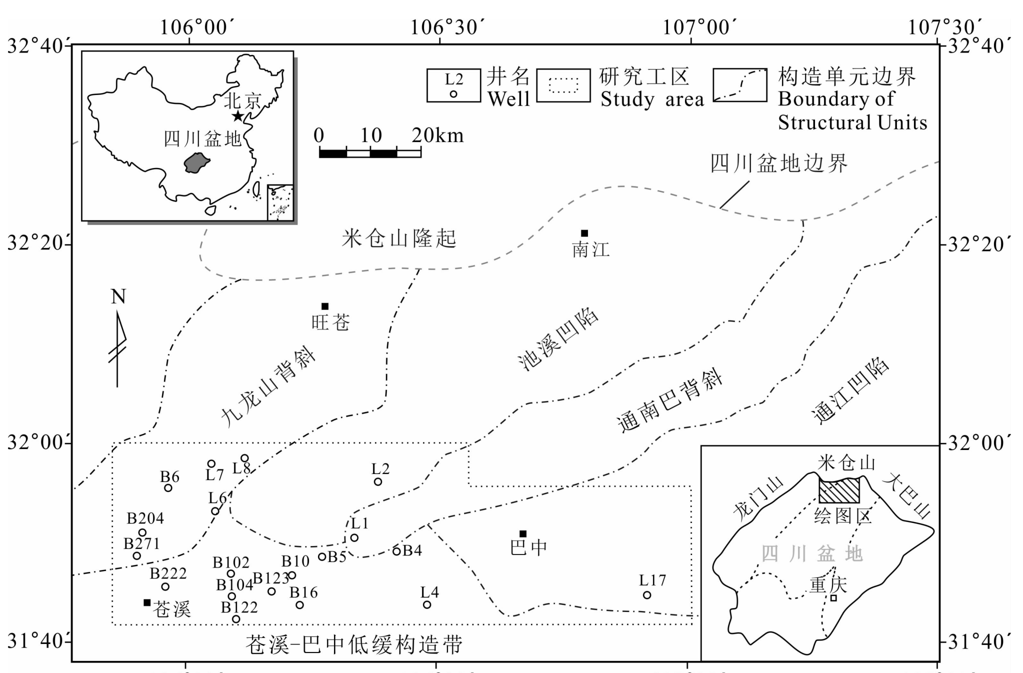

图 1 元坝地区构造位置图

Fig. 1 Structural location map of Yuanba area in NE Sichuan basin

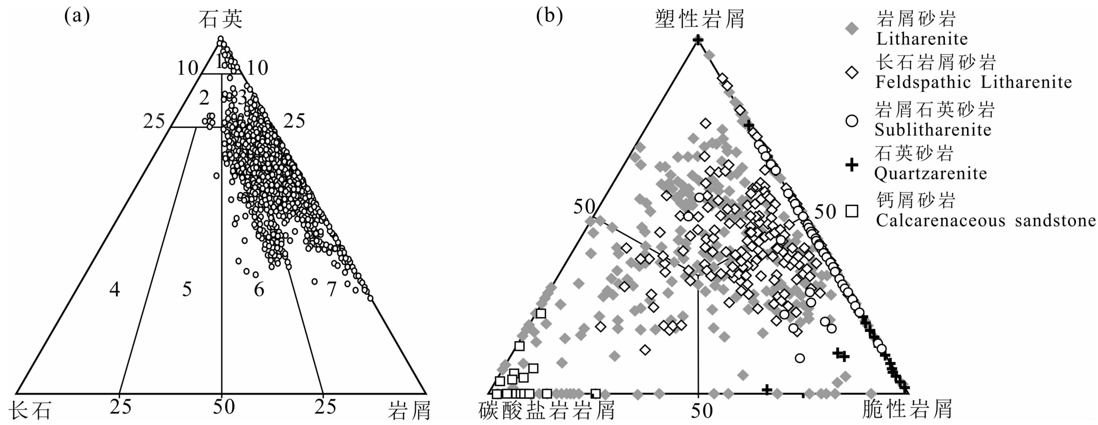

图 2　元坝地区须家河组砂岩碎屑组分含量和岩屑类型三角图(分类方案据 Folk，1974)

Fig. 2　A ternary diagram illustrating the detrital composition and the rock fragments composition of the Xujiahe sandstones, Yuanba area (classification scheme according to the reference Folk, 1974)

(a)—元坝地区须家河组砂岩碎屑组分含量三角图；(b)—元坝地区须家河组砂岩岩屑类型三角图；1—石英砂岩；2—长石石英砂岩；3—岩屑石英砂岩；4—长石砂岩；5—岩屑长石砂岩；6—长石岩屑砂岩；7—岩屑砂岩

(a) —The QFR ternary diagram of the Xujiahe sandstones, Yuanba area; (b)—the rock fragments composition ternary diagram of the Xujiahe sandstones, Yuanba area; 1—quartzarenite; 2—subarkose; 3—sublitharenite; 4—arkosic arenite; 5—lithic arkose; 6—feldspathic litharenite; 7—litharenite

和刚性岩屑，碳酸盐岩岩屑不发育。其刚性岩屑含量最高可达 17%，平均值为 11%；塑性岩屑含量最高可达 14%，平均值为 7.2%。钙屑砂岩的岩屑类型以碳酸盐岩岩屑为主，最高可达 77%，平均值为 57.3%。石英砂岩岩屑含量低，主要以抗压的刚性岩屑为主。

2.1.2　填隙物类型

研究区砂岩中的填隙物主要为原始沉积的杂基以及化学成岩过程中形成的钙质和硅质胶结物。通常细砂岩和粉砂岩中杂基含量较高(图 3A)，最高可达 40%，均值为 7.1%，多为河道侧缘和席状砂沉积。在杂基含量高的砂岩中，胶结作用不发育。钙质胶结物在研究区砂岩中也很常见，通常以充填孔隙和裂缝的形式出现，部分砂岩中可见方解石连晶胶结。较强的钙质胶结主要发育在富含钙屑的砂岩中，钙质呈基底式胶结，骨架颗粒呈悬浮状或点接触(图 3B)。砂岩中的硅质胶结物含量较低，最高仅达 12%，平均值为 1.3%。硅质胶结物常以石英加大(图 3C)和充填孔隙(图 3E)的形式出现。由于硅质胶结物通常在石英含量高、塑性岩屑和杂基含量低的高能环境砂岩中大量发育(Westcott, 1983)，而研究区砂岩岩屑和杂基含量高，因此，硅质胶结作用不发育，较强的硅质胶结作用仅在石英砂岩中可见。

受原始物质组分的影响，不同岩性砂岩的填隙物类型也不同(图 4)。岩屑砂岩和长石岩屑砂岩中，三种填隙物都发育，但以杂基和钙质胶结物为主。(岩屑)石英砂岩中，填隙物以硅质胶结物为主，其他类型的填隙物几乎不发育。钙屑砂岩中仅发育强钙质胶结，其他填隙物不发育。

2.2　孔隙结构特征

基于研究区 97 块铸体薄片和 50 块扫描电镜样品观察，砂岩孔隙类型以微孔隙为主(图 5A)。铸体薄片镜下大多数样品无可视孔隙，少数样品可见残余原生粒间孔(图 5B)和次生溶孔(岩屑溶孔和长石溶孔)(图 5B～D)。原生粒间孔通常与黏土薄膜伴生，孔径在 30～100μm 之间。溶蚀孔通常有原始物质残余，孔径在 5～25μm 之间。砂岩孔喉不发育或呈窄缝状，且喉道中有自生黏土矿物充填，降低连通性(图 5B)。这些原生孔和溶蚀孔仅在长石岩屑砂岩或岩屑砂岩中可见，而石英砂岩和钙屑砂岩中由于强烈硅质胶结和钙质胶结，孔隙不发育，即使在扫描电镜下也难以观察到孔隙的存在。

2.3　物性特征

元坝地区须家河组砂岩实测孔隙度为 0.48%～15.6%，主要分布区间为 1%～4%，平均值为 3.8%(图 7)。常压条件下实测渗透率为 $0.001\times10^{-3}\sim16.48\times10^{-3}\mu m^2$(包括裂缝渗透率)，主要分布区间为 $0.01\times10^{-3}\sim0.05\times10^{-3}\mu m^2$(图 7)。根据油气储层评价部颁标准(SY/T 6285-2011)，研究区砂岩以超低孔、超低渗为主，属于超致密砂岩(DOE, 1973)。与国内、外典型致密砂岩储层物性

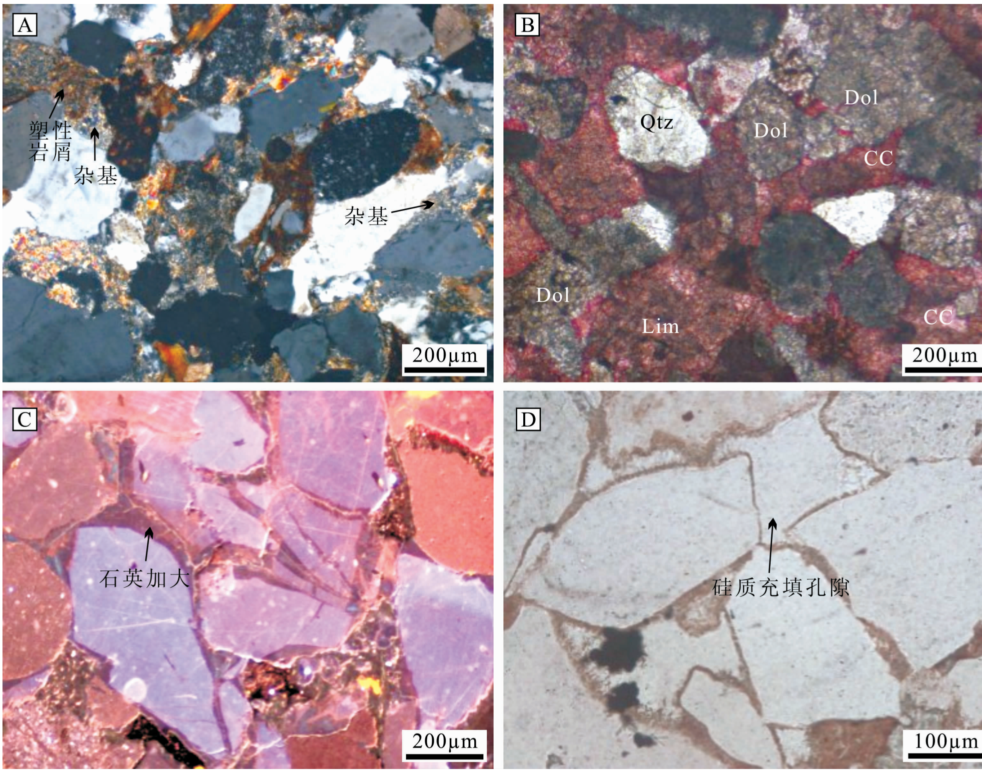

图 3 元坝地区须家河组砂岩显微镜与阴极发光照片

Fig. 3 Thin section and CL images showing interstitial materials of the Xujiahe sandstone in the Yuanba area

A—杂基和塑性岩屑压实变形强烈，杂基不规则充填孔隙空间，其他类型的填隙物不发育，岩屑砂岩，正交光，4277m，须二段，B271 井；B—方解石连晶式胶结，骨架颗粒以点—线接触为主，钙屑砂岩，单偏光，4610m，须二段，B2 井；C—石英加大边，形成于强压实之后，石英颗粒呈线—凹凸接触，岩屑石英砂岩，阴极发光，4297m，须二段，B271 井；D—硅质胶结充填孔隙式胶结，形成于强压实之后，骨架颗粒以线接触为主，岩屑石英砂岩，单偏光，4458.7m，须二段，L6 井；Qtz—石英颗粒；Dol—白云岩岩屑；Lim—灰岩岩屑；CC—钙质胶结物

A—The matrix and ductile fragments deforms as an irregular shape filling the intergranular pores and other interstitial materials were not developed, litharenite, crossed polars, 4277m, T_3x^2, well B271; B—sparry calcite cements interlock the micritic carbonate rock fragments and the detrital grains present as point to line contact, calcarenaceous sandstone, plainlight, 4610m, T_3x^2, well B2; C—quartz overgrowth formed after highly compaction and detrital quartz present as line to concave-convex contact, sublitharenite, cathodeluminescence, 4297m, T_3x^2, well B271; D—pore-filling quartz formed after highly compaction and detrital quartz present as line contact, sublitharenite, plainlight, 4458.7m, T_3x^2, well B6; Qtz—detrital quartz; Dol—dolomite rock fragments; Lim—limestone rock fragments; CC—calcite cement

表 1 元坝地区须家河组砂岩四类孔隙结构实测物性和孔隙结构参数(共统计 112 个平行样数据)

Table 1 The parameters of core measured property and pore structures for four types of the pore structure of the Xujiahe sandstones (112 parallel samples were counted)

孔隙结构	薄片镜下孔隙度（%）			实测物性		孔隙结构参数			
	原生孔	次生孔	面孔率	孔隙度（%）	渗透率（$\times10^{-3}\mu m^2$）	进汞压力（Psi）	分选系数	歪度	中值压力（Psi）
1				＜3	＜0.01	＞300	＜2	＜0.15	＞7000
2		＜1	＜1	3～5	0.01～0.05	100～300	2～2.4	0.15～0.4	4000～7000
3	＜1	＜5	＜6	5～8	0.01～0.05	100～300	2～2.4	0.15～0.4	2000～4000
4	＞2	＞5	＞7	＞8	0.05～1	＜100	＞2.4	＞0.4	＜500

相比，研究区砂岩的孔隙度和渗透率明显比其他致密砂岩气田低(图 7)，储集物性差，致密化程度高。从孔渗交汇图来看(图 8)，须家河组砂岩孔渗相关性一般，物性较好的砂岩主要为长石岩屑砂岩和岩屑砂岩。

3 砂岩超致密成因

砂岩的成岩过程导致了砂岩孔隙的损失，也就是砂岩致密化的过程。这一过程受沉积环境、物质组构以及埋藏历史等多方面原因控制(Bjørlykke,

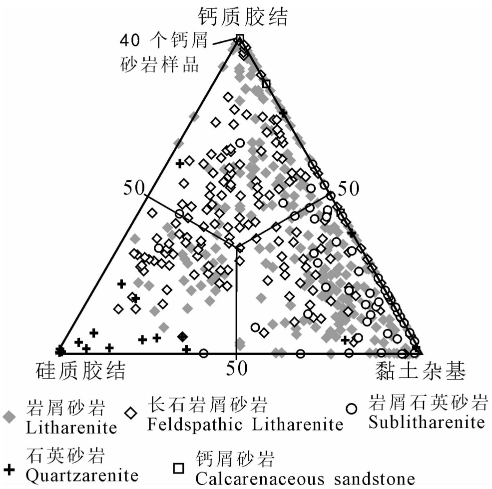

图 4　元坝地区须家河组不同岩性砂岩填隙物组成三角图

Fig. 4　A ternary diagram illustrating the interstitial material composition of the Xujiahe sandstones

2014),但对于封闭体系,砂岩的成岩作用则主要受原始物质组构和埋藏历史两方面的影响(Bjørlykke et al., 2012)。本文从物质组构和埋藏史两个方面,通过与国内外致密砂岩对比,揭示须家河组砂岩比其他砂岩致密化程度高的原因。

3.1　成岩对孔隙的影响

机械压实和胶结作用是砂岩孔隙损失的主要原因。Houseknecht(1987)首次提出了方法用来评估压实和胶结作用对砂岩孔隙损失的影响,但其计算公式没有考虑到压实过程中砂岩总体积的损失(Pate, 1989; Ehrenberg, 1989; Houseknecht, 1989; Lundegrad, 1992)。因此,本文采用Lundegard(1992)提出的公式来计算压实和胶结对孔隙损失的影响。计算结果表明,岩屑砂岩压实减孔强度平均值为81.8%,长石岩屑砂岩压实减孔强

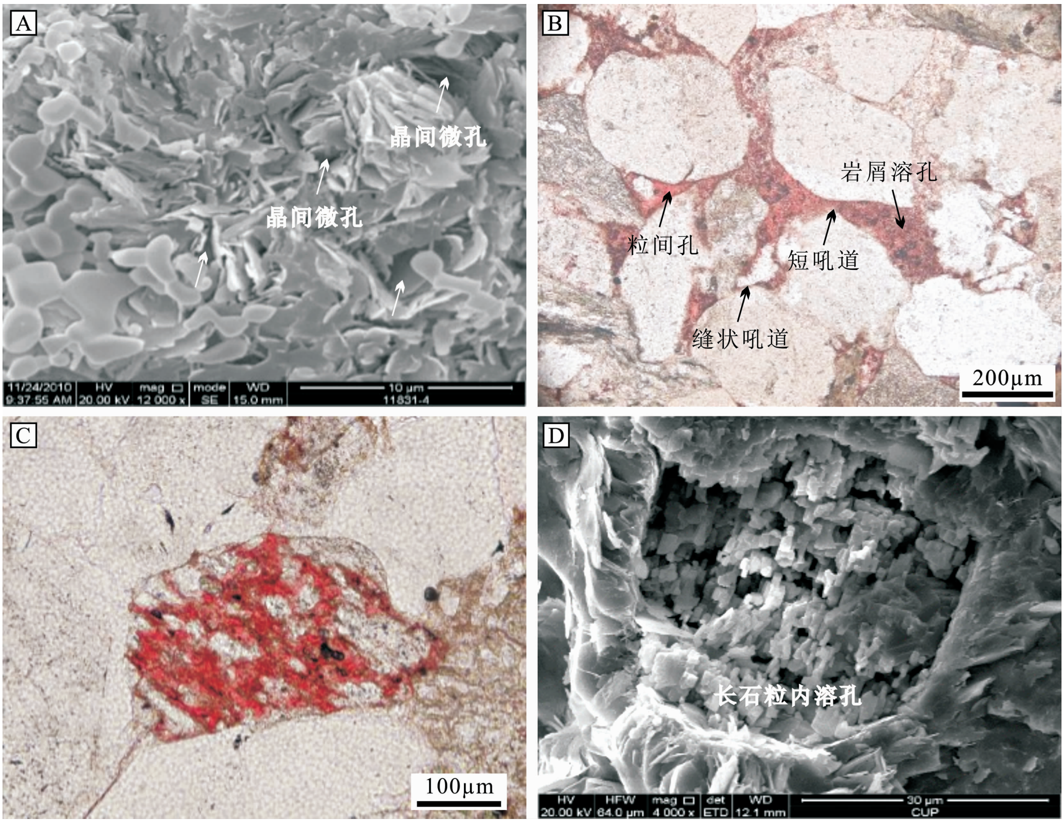

图 5　元坝地区须家河组砂岩孔隙类型显微镜与扫描电镜照片

Fig. 5　Thin section and SEM images showing the pore types in the Xujiahe sandstones, Yuanba area

A—伊蒙混层中发育黏土矿物晶间微孔隙,岩屑砂岩,扫描电镜,4927.96m,须二段,B2 井;B—原生粒间孔与岩屑溶孔,周围发育短喉道或缝状喉道连接孔隙空间,长石岩屑砂岩,正交光,4461.91m,须二段,L6 井;C—孤立的长石粒内溶孔,长石岩屑砂岩,单偏光,4623.32m,须四段,B16 井;D—孤立的长石粒内溶孔,沿节理溶蚀成梳齿状,扫描电镜,4473.78m,须二段,L6 井

A—Intercrystalline pores of the I/S mixed layer clay, litharenite, SEM, 4927.96m, T_3x^2, well B2; B—short or slot throts bridging the residual primary pores or lithic dissolution pores, feldspathic litharenite, crossed polars, 4461.91m, T_3x^2, well L6; C—isolated feldspathic dissolution pore, feldspathic litharenite, plainlight, 4623.32m, T_3x^4, well B16; D—feldspar dissolved along the joints and the dissolution pores fromed as a comb shape, SEM, 4473.78m, T_3x^2, well L6

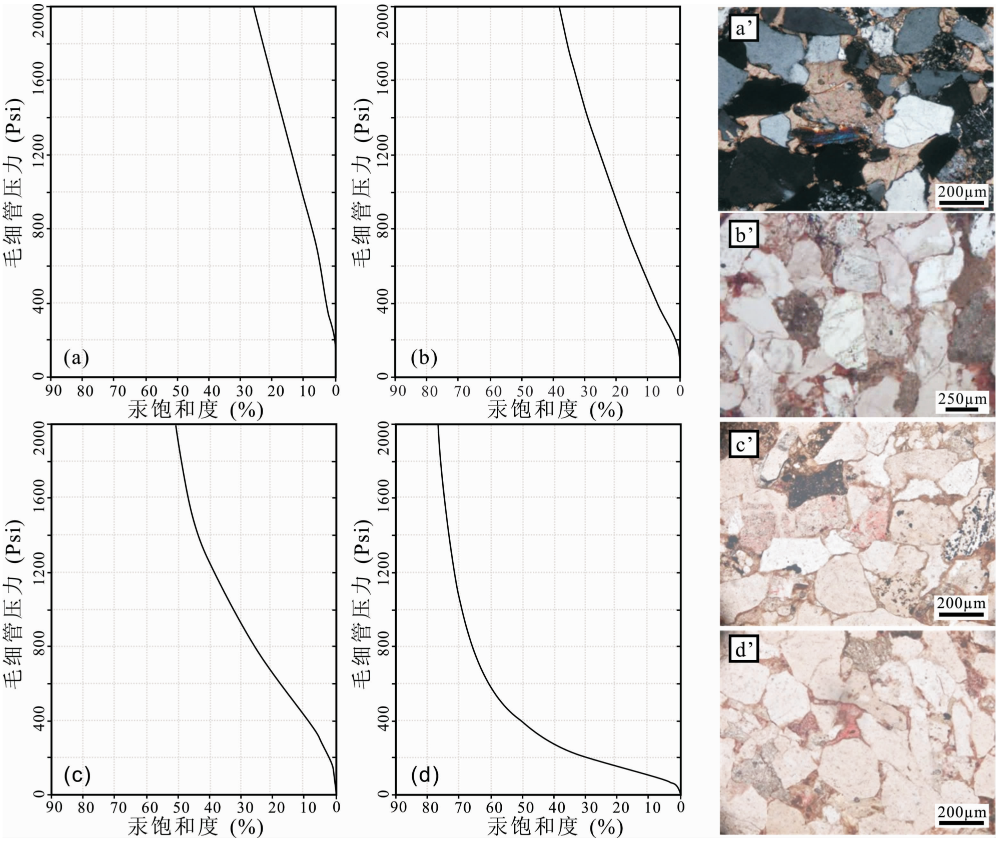

图 6 元坝地区须家河组四类孔隙结构压汞曲线图版和铸体薄片照片

Fig. 6 The capillary drainage curves and thin section images for four types of the pore structures of the Xujiahe sandstones

(a)和(a')—第一类孔隙结构:通常发育在钙屑砂岩和石英砂岩中,喉道分选差,偏细歪度,薄片中孔隙和喉道均不发育;(b)和(b')—第二类孔隙结构:通常发育在岩屑砂岩,长石岩屑砂岩和岩屑石英砂岩中,喉道分选差,偏细歪度,孔隙类型以微孔隙为主;(c)和(c')—第三类孔隙结构:通常发育在长石岩屑砂岩中,喉道分选差,偏细歪度,孔隙类型以孤立粒内溶孔为主;(d)和(d')—第四类孔隙结构:主要发育在长石岩屑砂岩中,喉道分选一般,偏粗歪度,可见原生粒间孔和溶蚀孔,且发育缝状喉道连通孔隙空间

(a) and (a')—Pore structure type I: this pore structure usually occurs at calcarenaceous sandstone or quartzarenite with the characteristics of poor throat sorting, small pore throat radius and poor connectivity, pores and throats can not be observed even in SEM; (b) and (b')—pore structure type II: this pore structure usually occurs at litharenite, feldspathic litharenite or sublitharenite with the characteristics of micropores and small pore throat radius; (c) and (c')—pore structure type III: this pore structure usually occurs at feldspathic litharenite with the characteristics of poor throat sorting, small pore throat radius and poor connectivity, the pore types are dominated by the isolated feldspar dissolution pore; (d) and (d')—pore structure type IV: this pore structure mainly occurs at feldspathic litharenite with the characteristics of moderate throat sorting and coarse pore throat, residual primary pores, secondary pores and slot pore throat can be observed in thin sections

度平均值为 70.5%,岩屑石英砂岩压实减孔强度平均值为 84.2%,石英砂岩的压实减孔强度平均值为 80.7%,钙屑砂岩的压实减孔强度平均值为 41.6%。由此可见,岩屑砂岩、长石岩屑砂岩、岩屑石英砂岩和石英砂岩孔隙度的减少主要受压实作用的影响,而钙屑砂岩孔隙度减少主要受强钙质胶结作用的影响(图 9)。

前人对机械压实和埋藏深度之间的关系做了大量研究(Selley, 1978; Zheng Junmao et al., 1996; Bjørlykke, 1999; Paxton et al., 2002),认为埋深小于 2000~2500m 时,压实作用对砂岩储集性能影响最强烈,原生孔隙急剧减小;当埋深超过 3000m 时,压实对砂岩储集性能的影响很小。研究区砂岩埋深小于 2500m 时,镜质组反射率低于 0.5%(Li Jun et al., 2012; Zhang Junwu et al., 2015),处于早成岩作用阶段。由于岩屑砂岩、长石岩屑砂岩、岩屑石英砂岩和石英砂岩主要受强烈压实作用影响导致储层孔隙的损失,据此推断,砂岩致密化时间较早,在早成岩阶段孔隙就已大量损失。钙屑砂岩主要受强烈钙质胶结作用导致孔隙的损失。强钙质胶结呈连晶式充填孔隙空间,砂岩骨架颗粒呈点接触(图 3B),说明钙屑砂岩致密化时间也较早,形成于早成岩阶段。Surdam et al.(1989)指出如果早期强烈压实作用使粒间孔隙损失或早期钙质胶结占据了

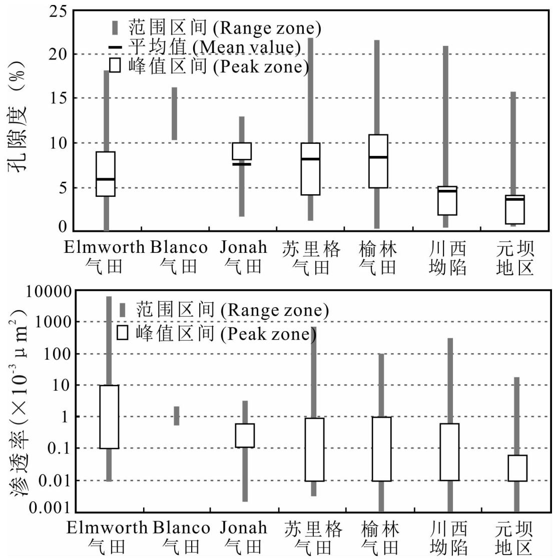

图 7　元坝地区须家河组与国内外致密砂岩气田储层物性对比图（物性数据据 Master，1979；Cant et al.，1984；Hietala et al.，1984；Pritchard，1984；Song Yan et al.，2001；Cluff et al.，2004；Fu Jinhua et al.，2005；Hu Mingyi et al，2006；Cui Yingchun et al.，2008；Guo Jianlin，2008；Yang et al.，2008；Ma Liyuan et al.，2009；Huang Qiang，2009；Xi Shengli et al.，2009；Liu Sibing，2010；Xie Qingbin，2011；Shi Lingling，2012）

Fig. 7　The comparison of reservoir property between the Xujiahe Formation in the Yuanba area and other tight gas sands (property data are cited from Master，1979；Cant et al.，1984；Hietala et al.，1984；Pritchard，1984；Song Yan et al.，2001；Cluff et al.，2004；Fu Jinhua et al.，2005；Hu Mingyi et al，2006；Cui Yingchun et al.，2008；Guo Jianlin，2008；Yang et al.，2008；Ma Liyuan et al.，2009；Huang Qiang，2009；Xi Shengli et al.，2009；Liu Sibing，2010；Xie Qingbin，2011；Shi Lingling，2012)

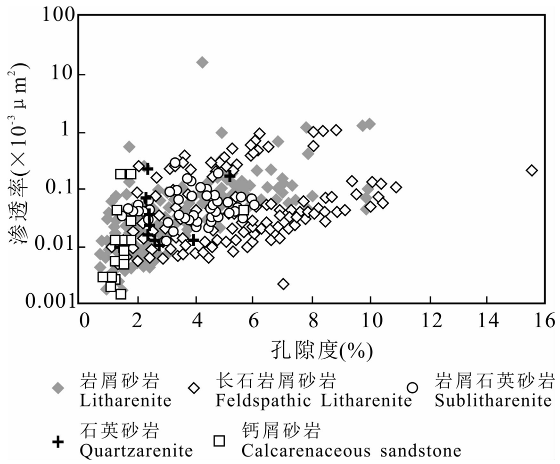

图 8　元坝地区须家河组不同岩性砂岩孔渗交汇图

Fig. 8　Cross plot of porosity and permeability for samples of various lithologies

大量粒间孔隙，那么砂岩将难以，甚至不会发生溶蚀作用。研究区大部分砂岩中未见溶蚀孔隙，只有少数砂岩中可见长石溶孔和岩屑溶孔（图 5B～D），且溶蚀孔中通常有原始物质残余，说明溶蚀作用弱。成岩早期的强压实、强钙质胶结使储层孔隙快速降低，中期的弱溶蚀使储层孔隙没有得到改善，再加上进一步的压实—压溶作用以及胶结作用，使得研究区砂岩强烈致密化。由此可见，成岩早期强烈压实作用和钙质胶结作用是导致研究区砂岩孔隙度极低的重要原因。

3.2　物质组构对比

砂岩的原始物质组构对砂岩的成岩过程具有控制作用，进而控制了砂岩的致密化程度。岩屑砂岩、长石岩屑砂岩和岩屑石英砂岩中通常含有较高塑性岩屑含量，在塑性岩屑含量较高的砂岩中，压实作用通常十分强烈，孔隙度和渗透率较低（Imam et al.，1985；Pittman et al.，1991；Worden et al.，2000）。Worden et al.（2000）指出富塑性颗粒的砂岩在压实作用下会发生塑性变形堵塞孔隙和喉道，使得其孔隙降低的速率高于富刚性颗粒的砂岩，由于喉道堵塞，渗透率也快速下降。因此，高杂基和塑性岩屑含量的砂岩，物性通常较差，成岩作用以强烈压实为主。在相同粒度条件下，砂岩中塑性岩屑含量越高越容易压实（Pittman et al.，1991）。研究区砂岩中具有较高的塑性岩屑含量（图 10b），而其他致密砂岩气田的岩屑含量较低（图 10a），即使是岩屑含量较高的 Great Green River 盆地 Jonah 气田和 San Juan 盆地 Blanco 气田，其岩屑类型也主要是以抗压的硅质岩岩屑和火山岩岩屑为主，塑性岩性含量较低（图 10b）。较高含量的塑性岩屑是导致岩屑砂岩、长石岩屑砂岩和岩屑石英砂岩压实作用强，致密化程度高的重要原因。

此外，较高的杂基含量也是研究区砂岩致密化程度高的另一个原因。其他地区砂岩的杂基含量均值都在 5% 以下，而研究区砂岩杂基含量均值为 7%，最高可达 43%（图 11）。较高含量的杂基导致砂岩的初始孔隙度低，且在压实作用的影响下，杂基易压实变形堵塞孔隙和喉道，使得砂岩快速致密化。研究区杂基大多伊利石化，可以促进石英颗粒压溶作用的进行（Bjørkum，1996），使得孔隙空间进一步减少。因此，较高含量杂基也是造成压实作用强烈，砂岩致密化程度高的原因。

石英砂岩中并没有较高的杂基和塑性岩屑含

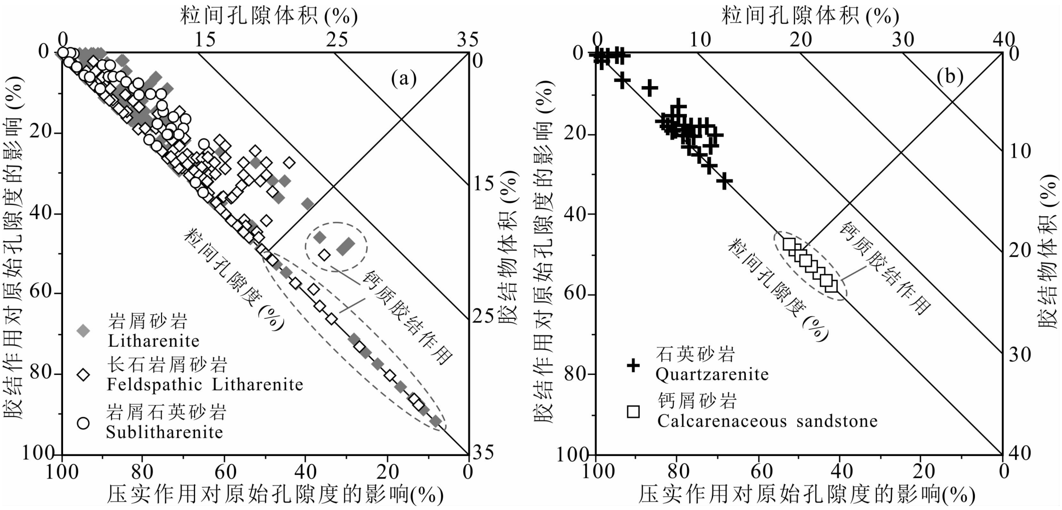

图 9 压实作用和胶结作用对须家河组砂岩孔隙影响评价图

Fig. 9 Diagram for evaluating the importance of compactional processes and cementation to porosity destroy in Xujiahe sandstone, Yuanba area

(a)—岩屑砂岩、长石岩屑砂岩和岩屑石英砂岩孔隙影响评价图,原始孔隙度 35%;
(b)—石英砂岩和钙屑砂岩孔隙影响评价图,原始孔隙度 40%

(a)—Diagram for evaluating the importance of compactional processes and cementation to porosity destroy in litharenite, feldspathic litharenite and sublitharenite with the primary porosity of 35%; (b)—diagram for evaluating the importance of compactional processes and cementation to porosity destroy in quartzarenite and calcarenaceous sandstone with the primary porosity of 40%

量,其强烈的压实作用与砂岩的岩石粒度有关。对石英砂岩而言,粒度是控制压实强度的主要因素,颗粒粒度越细,压实作用越强(Porter et al., 1986; Houseknecht, 1988)。研究区石英砂岩以极细粒—细粒为主,较细的岩石粒度是造成石英砂岩压实作用强烈的重要原因。

钙屑砂岩中钙质胶结物含量高,通常在 20%~26%之间,均值为 22%。强钙质胶结呈连晶式充填孔隙空间,是钙屑砂岩致密化的主要原因。Liu Sibing et al. (2014)对须家河组砂岩中碳酸盐胶结物的水-岩作用模式的研究表明,钙屑砂岩中的胶结物具有“自产自销”的特点,也就是说研究区砂岩中丰富的钙屑可以为钙质胶结提供大量的内部来源,且不需要大量的流体运移就可以发生钙质沉淀。因此,大量的钙屑是钙屑砂岩致密化的主要原因。

综上所述,原始物质组构是导致研究区砂岩比其他砂岩更致密的重要原因。研究区砂岩的高塑性岩屑含量、高黏土杂基含量、高钙屑含量以及石英砂岩较细的岩石粒度,是砂岩超致密化的物质基础。

3.3 埋藏史、热史对比

对比研究区与其他致密砂岩的埋藏史和热史(图 12),须家河组最大埋深超过 5000m,古地温超过 200℃,镜质组反射率(R_o)大于 2.0%。北美地区(Alberta 盆地、San Juan 盆地和 Great Green River 盆地)和鄂尔多斯盆地致密砂岩的最大埋深均小于 5000m,古地温均在 200℃以下,镜质组反射率(R_o)均小于 2.0%(Magara, 1976; Rice, 1983; Reiter et al., 1983; Welte et al., 1984; Bond, 1984; Tilley et al., 1989; Ren Zhanli et al., 1994; Montgomery et al., 1997; Coskey, 2004; Fu Jinhua et al., 2005; Ren Zhanli et al., 2006; Hou Mingcai et al., 2009;Bi Mingwei et al., 2015),比元坝地区须家河组的埋深浅、热演化程度低。也就是说,北美地区和鄂尔多斯盆地致密砂岩成岩演化阶段比研究区低,这是造成研究区砂岩比其他砂岩致密化程度高的另一重要原因。

4 勘探潜能

有效孔隙发育带是致密砂岩气富集和稳产的关键(Shanley et al., 2004; Cai Xiyuan, 2010),如 Alberta 盆地 Elmworth 气田,其天然气主要产自带状分布的砂质砾岩层(Masters, 1984),该套储层孔隙度主要分布在 8%~18%之间,渗透率通常大于 $1\times10^{-3}\mu m^2$,其含气饱和度高达 60%~80%,而周围致密砂岩的含气饱和度较低,通常低于 30%(Hietala et al., 1984)。鄂尔多斯盆地苏里格气田、榆林气田以及 San Juan 盆地 Blanco 气田也具有类似的情况。以苏里格气田为例,苏里格气田优质

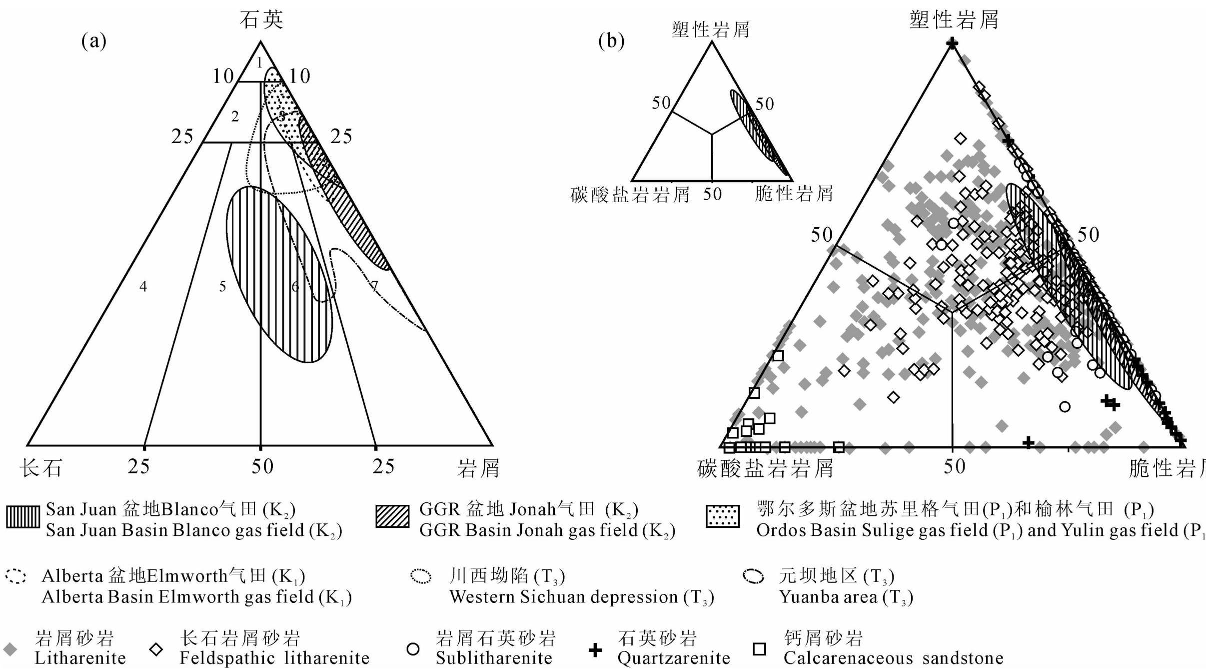

图 10　元坝地区须家河组砂岩与国内外典型致密砂岩碎屑组分和岩屑类型对比三角图

(数据据 Tilley et al., 1989; Loomis et al., 1996; Montgomery et al., 1997; Yang et al., 2008; Xi Shengli et al., 2009; Huang Qiang, 2009; Liu Sibing, 2010; Shi Lingling, 2012; Liu Ziwei, 2013)

Fig. 10　A ternary diagram comparing the detrital composition and the rock fragments composition between the Xujiahe sandstones and other tight sand reservoirs (data are cited from Tilley et al., 1989; Loomis et al., 1996; Montgomery et al., 1997; Yang et al., 2008; Xi Shengli et al., 2009; Huang Qiang, 2009; Liu Sibing, 2010; Shi Lingling, 2012; Liu Ziwei, 2013)

(a)—研究区与其他致密砂岩碎屑组分对比三角图;(b)—研究区与其他致密砂岩岩屑类型对比三角图;GGR—Great Green River;1—石英砂岩;2—长石石英砂岩;3—岩屑石英砂岩;4—长石砂岩;5—岩屑长石砂岩;6—长石岩屑砂岩;7—岩屑砂岩

(a)—Ternary diagram comparing the detrital composition between the Xujiahe sandstones and other tight sand reservoirs; (b)—ternary diagram comparing the rock fragments composition between the Xujiahe sandstones and other tight sand reservoirs; GGR—Great Green River; 1—quartzarenite; 2—subarkose; 3—sublitharenite; 4—arkosic arenite; 5—lithic arkose; 6—feldspathic litharenite; 7—litharenite

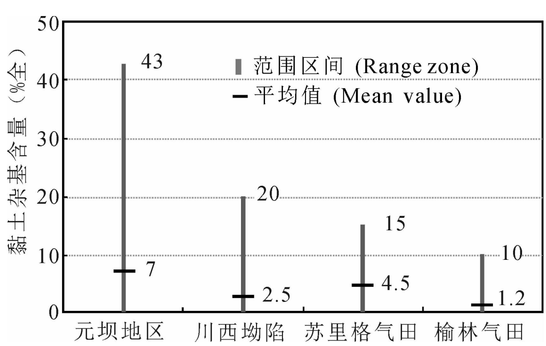

图 11　元坝地区须家河组与其他致密砂岩气田砂岩黏土杂基含量对比图(数据据 Chen Zhaorong, 2009; Xi Shengli et al., 2009; Dai Chaocheng et al., 2011; Liu Ziwei, 2013)

Fig. 11　Compare the content of the clay matrix in Xujiahe sandstones, Yuanba area with other tight sand reservoirs (data are cited from Chen Zhaorong, 2009; Xi Shengli et al., 2009; Dai Chaocheng et al., 2011; Liu Ziwei, 2013)

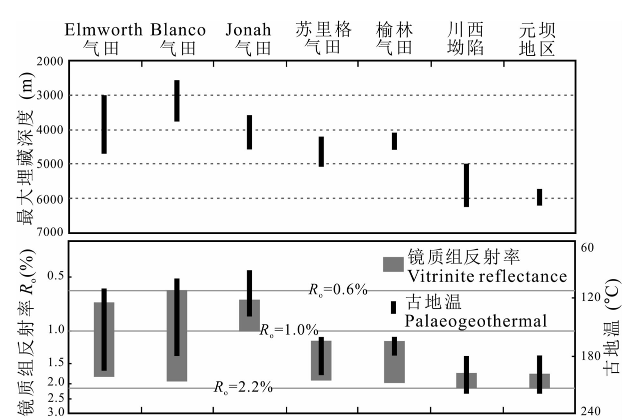

图 12　元坝地区须家河组与其他致密砂岩气田最大埋深和热演化程度对比图

Fig. 12　The comparison of maximum burial depth and thermal evolution between the Xujiahe Formation in Yuanba area and other tight sand gas reservoirs

储层发育带孔隙度通常在 8%～15%之间,渗透率一般大于 $0.1\times10^{-3}\,\mu m^2$,天然气单井开发无阻流量通常大于 $1\times10^4\,m^3/d$,甚至可高达 $10\times10^4\,m^3/d$;而致密砂岩储层孔隙度一般小于 5%,渗透率小于 $0.1\times10^{-3}\,\mu m^2$,天然气单井无阻流量一般小于 1×

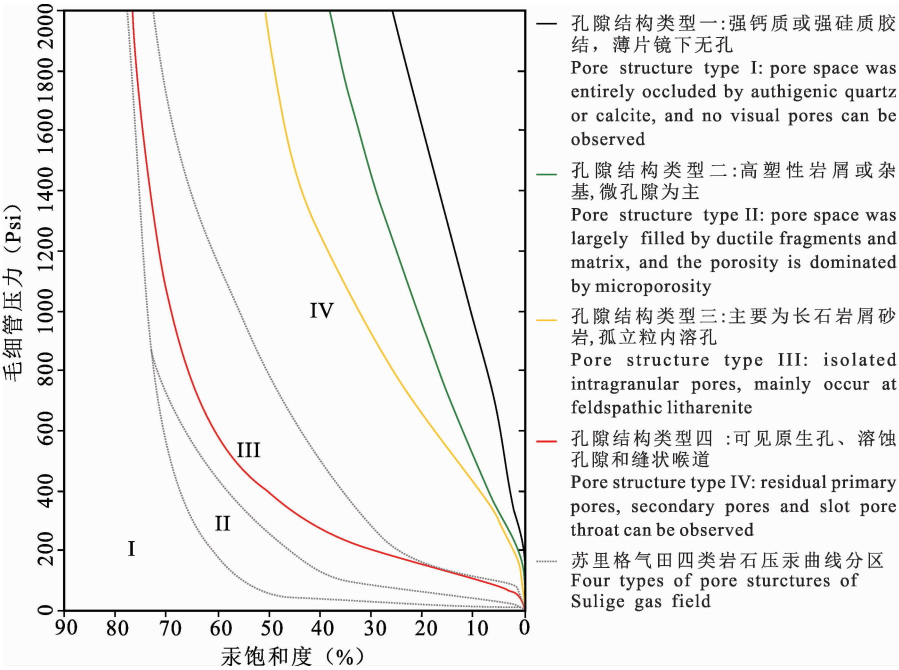

图 13　基于苏里格气田四类砂岩压汞曲线分区图版，对比元坝地区须家河组砂岩压汞曲线类型

Fig. 13　Compared the capillary drainage curves of the Xujiahe sandstones with the capillary drainage curves for four types of rocks in Sulige gas field of Ordos basin

10^4 m^3/d(Yang et al., 2008; Zhao Wenzhi et al., 2013)。

Yang et al.(2008)将苏里格气田的储层岩石类型划分为四类(图 13):I 类和 II 类岩石在没有天然裂缝或人工压裂的情况下具有经济产能,III 类岩石在有天然裂缝或者人工压裂的情况下具有经济产能,IV 类岩石即使有天然裂缝或人工压裂的情况下也不具有经济产能。与苏里格气田储层岩石压汞曲线相比,研究区砂岩最好的孔隙结构类型相当于苏里格气田 III 类岩石的孔隙结构,没有岩石属于苏里格气田的 I 类和 II 类岩石,大部分砂岩的孔隙结构类型属于苏里格气田的 IV 类岩石的孔隙结构。由此可见,元坝地区须家河组只有孔隙度近于 8%(如长石岩屑砂岩)的砂岩才可成为有利的致密气储层。

5　结论

(1)元坝地区须家河组砂岩具有较高含量的塑性岩屑、钙屑和杂基含量,决定了早成岩致密化、中成岩超致密化的物质基础。

(2)研究区砂岩致密化过程分为早成岩致密和中成岩超致密两个阶段:一是较高含量的塑性岩屑、黏土杂基和钙屑导致早成岩阶段强烈的压实和钙质/黏土胶结作用,从而致密化时间早,溶蚀作用弱;二是埋深大,砂岩经历了中成岩阶段的压溶及其伴生的再次钙质/硅质胶结作用。

(3)超致密砂岩有效孔隙少,对天然气的富集能力有限,大部分砂岩以黏土矿物晶间微孔隙为主,喉道不发育或呈窄缝状。元坝地区须家河组只有孔隙度近于 8%(如长石岩屑砂岩)的砂岩才可成为有利的致密气储层。

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Characteristics and Densification Causes and of Highly-Tight Sandstone of the Xujiahe Formation (T_3x^2) in the Yuanba Area, Northeastern Sichuan Basin

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Abstract

The Xujiahe sandstones in the Yuanba area are characterized by ultra-low porosity and ultra-low permeability and should belong to ultra-compacted sandstone. Based on thin sections, cathodeluminescence (CL), scanning electron microscope (SEM) and reservoir property data, densification causes and exploration potential are unraveled through comparison of detrital components, interstitial materials and reservoir properties between the Xujiahe sandstones and other tight sands in the world. The results show that the Xujiahe sandstones contain high contents of ductile rock fragments, clay matrix and carbonate fragments. The interstitial materials are dominantly clay matrix and calcite cements, with strong siliceous cementation occurring in quartz sandstone. Secondary pores are dominated by clay matrix intercrystalline micropores, with pore throats commonly present as narrow, poor sorting and sheetlike slots. There are two reasons for the highly densification of the Xujiahe sandstones. First, the anomalously poor quality of sandstones is attributed to the high compaction and calcite cementation during the early diagenetic stage, which are functions of the primary texture and composition of sandstones. Second, the Xujiahe sandstones were buried deeply and experienced further compaction and calcitic/siliceous cementation to forming highly tight sandstone in mesogenetic stage. Comparison with typical tight sandstone gas abroad indicates that ultra-tight sandstone contain less effective porosity, which has limited accumulation capacity to nature gas. Therefore, only when the porosity of the Xujiahe in the Yuanba area reaches to 8% (e.g. feldspathic litharenite) can sandstone be favorable reservoir for highly-tight sandstone exploration.

Key words: rock components; pore structures; reservoir property; Xujiahe Formation; Yuanba area