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鄂尔多斯盆地西南部三叠系延长组 7 段页岩层系层理缝发育特征与主控因素

卢　晧[1,2]，张皎生[3,4]，李　超[3,4]，曾联波[1,2]，刘艳祥[1,2]，吕文雅[1,2]，李睿琦[3]

1.中国石油大学(北京) 油气资源与工程全国重点实验室，北京　102249；
2.中国石油大学(北京) 地球科学学院，北京　102249；
3.中国石油 长庆油田分公司 勘探开发研究院，西安　710018；
4.低渗透油气田勘探开发国家工程实验室，西安　710018

摘要：鄂尔多斯盆地西南部三叠系延长组 7 段(以下简称长 7)页岩层系中层理缝普遍发育，对该区甜点优选、压裂施工和开发部署等具有重要意义。通过对盆地西南部庆城—华池地区的地表露头和岩心观察，结合其有机质含量、矿物组分和纹层特征等分析测试资料，明确了长 7 页岩层系不同岩性中层理缝的发育特征，并分析了该区层理缝发育的主控因素。研究结果表明，鄂尔多斯盆地西南部研究区长 7 页岩中层理缝的形态和分布主要受纹层控制，因纹层特征的不同而呈现连续平直、波状弯曲、分叉等特征。砂岩层理缝大多顺黑云母纹层分布，连续性好，开度大，普遍未被充填，而页岩层理缝在黑色页岩中发育程度最高，多沿有机质纹层构成的页理面分布，少数被方解石、有机质局部或完全充填，开度较砂岩更小但密度更大。层理缝还受有机质含量、岩性、矿物组分、纹层结构的控制。砂岩层理缝主要受黑云母含量及其形成的纹层控制，当砂岩分选好、黑云母含量多且呈层状分布时，层理缝发育程度高。随着纹层密度的增加，层理缝的发育程度随之增加，而页岩层理缝主要发育于有机质纹层和凝灰质纹层中，受有机质含量及矿物组分控制，层理缝密度随纹层密度先增加后降低，薄纹层较厚纹层中层理缝密度更高。

关键词：页岩油；层理缝；发育特征；主控因素；长 7；鄂尔多斯盆地

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Development characteristics and main controlling factors of bedding-parallel lamellated fractures in shale in 7th member of Triassic Yanchang Formation，southwestern Ordos Basin

LU Hao[1,2]，ZHANG Jiaosheng[3,4]，LI Chao[3,4]，ZENG Lianbo[1,2]，LIU Yanxiang[1,2]，LÜ Wenya[1,2]，LI Ruiqi[3]

1. *National Key Laboratory of Petroleum Resources and Engineering，China University of Petroleum（Beijing），Beijing* 102249，*China*；
2. *College of Geoscience，China University of Petroleum（Beijing），Beijing* 102249，*China*；
3. *Research Institute of Exploration and Development，PetroChina Changqing Oilfield Branch Company，Xi'an，Shaanxi* 710018，*China*；
4. *National Engineering Laboratory for Exploration and Development of Low Permeability Oil and Gas Fields，Xi'an，Shaanxi* 710018，*China*

Abstract：Bedding-parallel lamellated fractures are widely developed in shale in the 7th member of Triassic Yanchang Formation（hereinafter referred to as Chang 7）in the southwestern Ordos Basin，which holds significant importance for sweet spot selection，fracturing operations，and development planning. In this paper，based on the

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作者简介：卢晧(1994—)，男，博士生，主要从事页岩油储层多尺度裂缝形成机理与分布模式研究。E-mail：luhao123hn@163.com。

通信作者：曾联波(1967—)，男，博士，教授，主要从事储层裂缝形成、分布及预测以及非常规储层评价与预测研究工作。E-mail：lbzeng@sina.com。

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surface outcrop and core observations in the Qingcheng to Huachi region of the southwestern basin, combined with analysis and testing of organic matter content, mineral composition and fabric characteristics, the developmental characteristics of bedding-parallel lamellated fractures in different lithologies in the Chang 7 shale were identified, and the main controlling factors of fracture development were analyzed. Results show that the morphology and distribution of the bedding-parallel lamellated fractures are mainly controlled by the laminates, exhibiting characteristics such as continuous flatness, wavy bending and branching due to the different characteristics of the laminae. Sandstone bedding-parallel lamellated fractures are mostly distributed along the biotite laminae, with good continuity and large aperture, and are generally unfilled. Shale bedding-parallel lamellated fractures are most developed in black shale, mostly distributed along the bedding laminates composed of organic matter layers, with a few partially or completely filled by calcite and organic matter. The aperture is smaller than that of sandstone, but the density is higher. Bedding-parallel lamellated fractures are also controlled by organic matter content, lithology, mineral composition, and laminate structure. The sandstone bedding-parallel lamellated fractures are mainly controlled by the content of biotite and the laminates formed by it. When sandstone sorting is good and biotite content is high with a layered distribution, the degree of fracture development is high. As the density of the laminates increases, the degree of development of bedding-parallel lamellated fractures also increases. Shale bedding-parallel lamellated fractures mainly develop in organic matter laminates and tuffaceous laminates, and are controlled by organic matter content and mineral components. Fracture density increases first and then decreases with the density of the layers. Fracture density in thin laminates is higher than that in thick laminates.

Key words: shale oil; bedding-parallel lamellated fracture; development characteristics; main controlling factors; 7th member of Yanchang Formation; Ordos Basin

页岩油作为走向近源、源内的新兴非常规石油资源,具有巨大的勘探开发潜力,已在国内各大沉积盆地中取得重大发现[1-2],如鄂尔多斯盆地三叠系延长组长 7 页岩油、松辽盆地白垩系青山口组、嫩江组古龙页岩油、准噶尔盆地二叠系芦草沟组页岩油等。页岩油赋存于泥页岩及近源的致密砂岩、碳酸盐岩等夹层组成的页岩层系中[3],这类储层具有极低的基质孔隙度和渗透率,天然裂缝普遍发育。天然裂缝是页岩油的重要储集空间和渗流通道,因此,天然裂缝对页岩油开发至关重要[4-6]。层理缝是岩石在沉积和成岩过程中形成的沿层理分布的天然裂缝,作为页岩油储层中重要的天然裂缝类型,既显著提高了储层的储集和渗流能力,也影响了压裂缝的扩展延伸,最终影响页岩油的富集和高产[7-11],因此,阐明层理缝发育特征和主控因素,对页岩油富集、高效开发的理论及关键技术研究具有重要地质意义。

前人在对各大盆地油气储层的裂缝研究中,普遍发现了层理缝,并对其形态特征、发育规律等做了大量表征[12-18]。也有越来越多的研究注意到层理缝不仅控制了高产,还促进了油气的运移和富集[9,19-20]。前人研究认为层理缝的形成与构造、成岩、异常流体压力等因素相关,在不同的盆地和地层中存在差异[21-31]。正是由于成因的多样性,对于控制层理缝发育的地质因素仍然未取得共识。已有的相关研究大多针对南方海相页岩,认为层理缝与有机质含量、矿物组成、纹层结构相关,然而对于陆相页岩中层理缝主控因素的认识仍然不明确[27,32-35]。

早期勘探开发研究认为构造裂缝是影响鄂尔多斯盆地致密油气运移、富集和开发的主要裂缝类型[36],对层理缝研究较少。近年来逐渐有学者对鄂尔多斯盆地长 7 页岩层系致密砂岩层理缝进行了研究,并认为层理缝在致密油储层中主要发挥储集作用[9-11]。然而已有勘探开发实践表明,层理缝广泛发育在长 7 页岩层系的各类岩相中,层理缝发育的纹层型页岩油已经成为区内主要勘探开发对象[11,37-38],层理缝的存在大大提升了页岩油储层含油性以及流体可流动性。然而其强烈的非均质性使得层理缝的表征和预测变得非常困难[11,39-40],因此,明确层理缝的发育特征和主控因素,对于长 7 页岩油甜点优选、压裂施工和开发部署都具有重要意义。通过对庆城—华池一带的地表相似露头、岩心分析和薄片镜下观察,刻画了不同岩性中层理缝发育特征,并结合储层的有机质含量、矿物组分和纹层特征,探讨了层理缝发育的影响因素。

1　研究区地质概况

鄂尔多斯盆地位于华北地台西部,为在印支运

动控制下发育的大型内陆坳陷湖盆[41]。盆地从古生代至今经历了多期构造沉降和抬升，现今构造相对稳定，呈西南翼陡倾而东北翼宽缓的不对称单斜形态，由西缘冲断带、天环坳陷、伊陕斜坡、晋西挠褶带、伊盟隆起及渭北隆起 6 个二级构造单元组成[42]，本次研究取心井分布于天环坳陷南段至伊陕斜坡西南部一带(图 1a-b)。

鄂尔多斯盆地在中—晚三叠世经历了拗陷、扩张到消亡的完整演化过程，沉积了延长组陆相地层[43]。其中，长 7 段沉积于湖盆鼎盛时期，三角洲退缩至湖盆边缘，在盆地中心发育半深湖—深湖、前三角洲亚相泥岩和黑色页岩[44]。随着湖盆萎缩和三角洲的前积，伴随着同期秦岭造山运动引发的地震活动，三角洲沉积物失稳，并引发频繁的重力流事件，在湖盆中部庆城—华池一带沉积连片的重力流砂体，构成了长 7 页岩油储层的主体[45-46]。在最大湖泛期发育的长 7_3 亚段以黑色页岩、暗色泥岩为主，夹薄层深灰色及灰色粉砂岩，底部夹多层不等厚的凝灰岩[47-49]。长 7_2 至长 7_1 亚段则表现为暗色泥岩和灰色、灰绿色细砂岩互层，湖盆中心的重力流砂体多为中厚层块状构造或薄层粒序层理，湖盆边缘三角洲砂体则普遍发育交错层理和平行层理[44,50-51](图 1c)。

长 7 段各类岩性中纹层结构普遍发育，长英质(砂质、粉砂质)纹层、黏土纹层、有机质纹层、凝灰质纹层构成了半深湖—深湖区主要的纹层类型，尤以长 7 段中下部粉砂质泥岩、泥页岩中纹层最为密集[52-53]。不同岩性储层发育的纹层类型存在差异，细砂岩和粉砂岩中主要发育砂质纹层，有机质纹层、黏土纹层较少。在湖盆东北部三角洲前缘砂岩中，黑云母是一类重要的填隙物[54]，也常沿平行层理和交错层理面聚集构成极薄的黑云母纹层。粉砂质泥岩则以粉砂质纹层、黏土纹层和有机质纹层为主。泥页岩多由黏土纹层、有机质纹层叠置而成，局部发育凝灰质纹层。这些纹层类型在垂向上以不同的厚度和频率互相叠置，形成不同的纹层组合，进而构成长 7 段各类岩性储层[38,53]。

2 层理缝发育特征

2.1 砂岩层理缝

长 7 页岩层系中，重力流成因的砂岩普遍为块状构造，因而层理缝极少发育。少数岩心上可见到水平延伸的层理缝断续分布，横向规模较小(小于7 cm)，肉眼无法观测到开度，但当砂岩含油

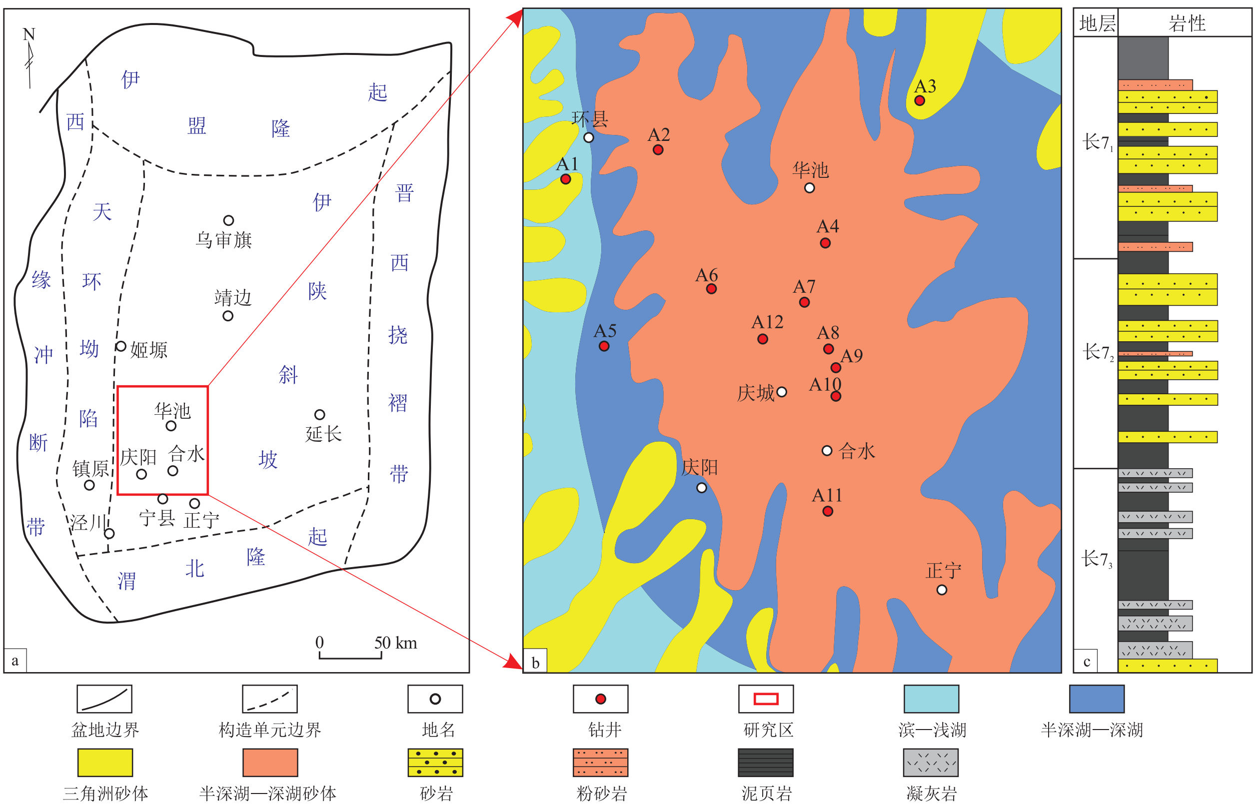

图 1 鄂尔多斯盆地构造单元(a)、研究区沉积相分布(b)及延长组 7 段地层柱状图(c)[55-56]

Fig.1 Structural units (a), sedimentary facies distribution of study area(b) and stratigraphic column of Chang 7 member (c) in Ordos Basin

时,原油往往沿层理缝渗出,呈现线状或串珠状油迹(图 2a),指示其具有一定的开度,不同于未裂开的层理。三角洲前缘的砂岩中各类交错层理和平行层理较为发育,这些层理面普遍富集黑云母,岩心极容易沿其破裂,局部被有机质充填。镜下观察显示这些黑云母长轴沿水平方向分布,横向上相互叠接延伸,纵向上多层黑云母叠置形成不同厚度的纹层,层理缝即沿这些黑云母纹层发育于纹层内部或纹层边界(图 2b)。通常,层理缝沿着相邻黑云母颗粒的接触面裂开,而在一些粒径较大的黑云母构成的纹层中,层理缝亦可沿黑云母解理面发生破裂(图 2c)。当砂岩内黑云母发育,但分布较分散,不以纹层形式出现时,层理缝沿黑云母发生破裂,但延伸长度更短,且易发生弯曲、分叉,开度也随局部黑云母含量变化而变化。砂岩中的有机质纹层同样发育层理缝,这些有机质纹层具有良好的连续性,但形态起伏更大,层理缝随着纹层发生弯曲变形、减薄尖灭。此外,由于庆城—华池地区长 7 沉积期重力流沉积现象普遍,在砂岩内部常见泥岩撕裂屑,呈现砂包泥特征,薄片下观察到层理缝沿泥岩撕裂屑边缘或内部发育,并严格受泥岩撕裂屑形态、大小及延伸性控制。

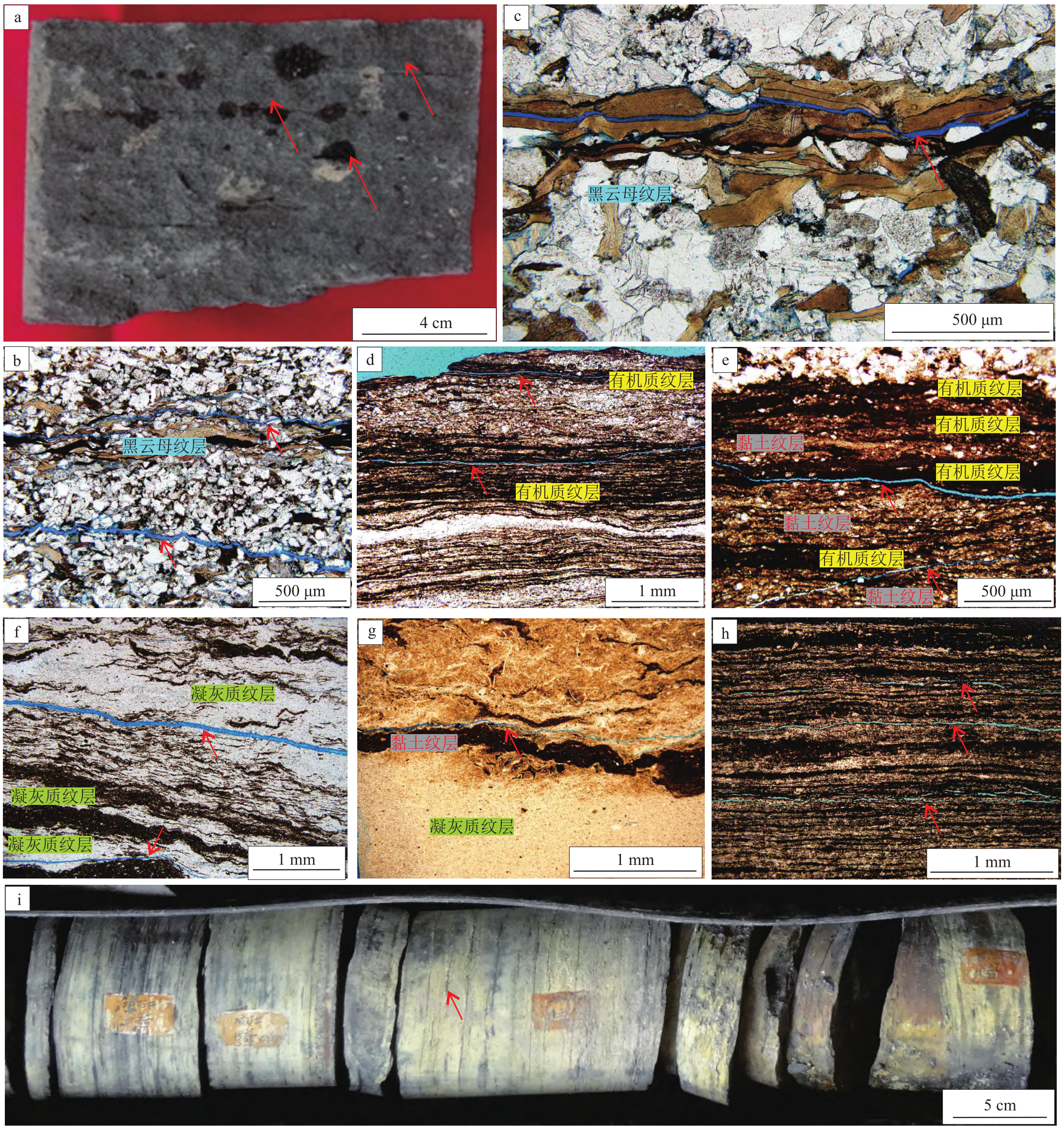

图 2　鄂尔多斯盆地西南部延长组长 7 页岩层系层理缝形态特征

a.细砂岩中原油沿层理缝渗出,呈串珠状油迹,A11 井,1 666.0 m;b.粉砂岩层理缝沿黑云母纹层发育,A3 井,1 995.2 m;c.细砂岩层理缝沿黑云母解理发育,A3 井,2 019.2 m;d.粉砂质页岩层理缝沿有机质纹层发育,形态平直,A9 井,1 931.3 m;e.粉砂质页岩层理缝沿有机质纹层发育,随纹层弯曲变形,A8 井,1 960.1 m;f.与黏土共生的凝灰纹层中的层理缝,A4 井,1 963.2 m;g.凝灰纹层中的层理缝,A5 井,2 470.6 m;红色箭头均指示层理缝;h.泥页岩层理缝沿有机质纹层发育,形态平直,A2 井,2 165.2 m;i.凝灰质泥页岩,A12 井,2 092 m。

Fig.2　Morphological characteristics of bedding-parallel lamellated fractures in Chang 7 shale system in southwestern Ordos Basin

本文观察到的砂岩样品中层理缝大多未被充填(图 3a),部分层理缝被黑色有机质全充填或局部充填。对未被充填层理缝镜下开度进行统计,通过围压校正至地下的砂岩层理缝开度集中分布于0~10 μm,占所有砂岩层理缝的 85%以上,仅少数样品中观察到层理缝开度介于 10~20 μm,最大值为35 μm(图 4a)。层理缝密度分布于 0~0.8 条/mm之间,以 0~0.6 条/mm 为主,占总数的 87.5%(图5a)。砂岩中层理缝虽开度不大,但因普遍未被充填,依然可以成为有效裂缝沟通流体。尤其在一些强溶蚀层段,层理缝将孤立的溶蚀孔连通,显著改善了储层的渗流能力。

2.2 页岩层理缝

长 7 段发育的页岩以深湖—半深湖黑色页岩为主体,夹有暗色泥岩和薄层凝灰岩夹层。在不同的岩相中,由于层理构造发育程度存在显著差异,层理缝的发育程度和特征亦存在区别。暗色泥岩以黏土矿物和泥级碎屑矿物颗粒为主,夹有粉砂质纹层,其有机质含量较低,多以纹层形式集中赋存于黏土中,层理缝普遍沿这些有机质纹层发育,随着有机质纹层的横向尖灭,部分层理缝会继续延伸至黏土中。由于泥页岩层理构造较弱,层理缝常常出现弯曲、转向或终止,因此其延伸规模相对较小。

黑色页岩以极薄的有机质纹层和黏土纹层叠置而成,页理构造相当发育。这些薄纹层多数平直且横向延伸非常稳定、连续性较好(图 2d),有利于层理缝(页理缝)发育。部分页岩同时发育粉砂质纹层或细砂岩透镜体,指示了短时间内的水体扰

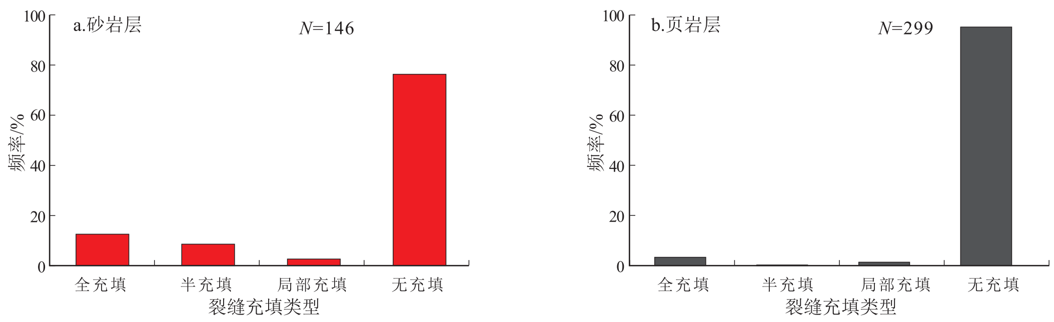

图 3 鄂尔多斯盆地西南部延长组长 7 页岩层系层理缝充填特征

Fig.3 Filling properties of bedding-parallel lamellated fractures in Chang 7 shale system in southwestern Ordos Basin

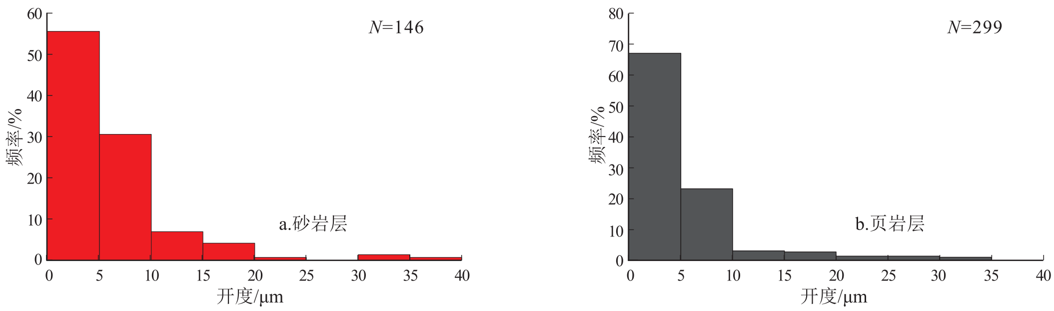

图 4 鄂尔多斯盆地西南部延长组长 7 页岩层系层理缝开度分布

Fig.4 Aperture of bedding-parallel lamellated fractures in Chang 7 shale system in southwestern Ordos Basin

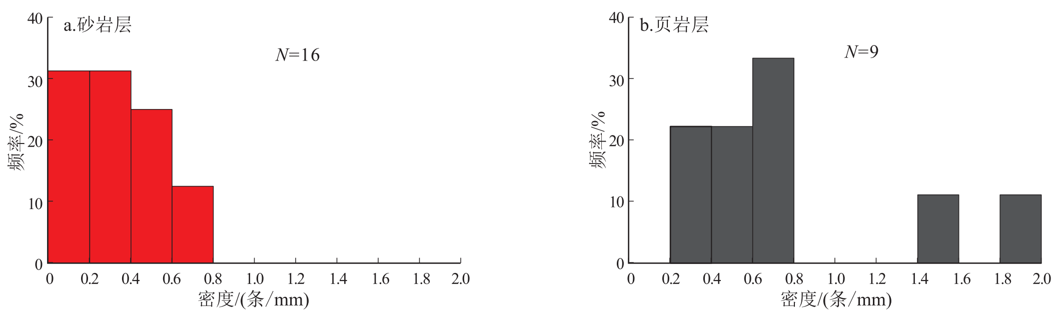

图 5 鄂尔多斯盆地西南部延长组长 7 页岩层系层理缝密度分布

Fig.5 Density of bedding-parallel lamellated fractures in Chang 7 shale system in southwestern Ordos Basin

动,与其共生的有机质或黏土纹层形态出现弯曲、分叉,层理缝沿有机质或黏土纹层发育(图 2e)。页岩层理缝受有机质纹层形态控制,层理缝大多平直且连续,横向开度相对稳定。当页岩中发育凝灰质纹层时,层理缝多发育在凝灰质纹层内部。这些凝灰质纹层以玻屑和晶屑为主,也可见少量岩屑,结构和构造差异较大。当凝灰质纹层与黏土纹层叠置时,层理缝更发育、延伸性更好(图 2f),在相对均质的凝灰岩中,层理缝发育程度较低,形态存在一定程度的弯曲,但延伸性差(图 2g),无论纹层构造如何,凝灰质纹层发育的页岩层理缝发育程度最高。

泥页岩约有 97%的层理缝未被充填,少数被方解石、有机质局部或完全充填(图 3b)。页岩层理缝的开度分布与砂岩相似,校正至地下围压后,约 89%的层理缝开度小于 10 μm(图 4b)。层理缝密度分布则与砂岩存在显著差异,其主体依然为 0.2~0.8 条/mm,但同时存在部分层理缝高度发育的页岩,其密度可达 1.4~2 条/mm(图 5b),这些样品包括页理密集的黑色页岩和凝灰质纹层高度发育的凝灰岩夹层。因此,页岩层理缝发育程度较砂岩更高,且非均质性更强,同时部分层理缝已被充填成为无效裂缝,对其有效性造成影响。

3　层理缝发育控制因素

层理缝由成岩作用、构造应力或异常高压等外部动力驱动作用下,沿以层理为代表的岩石力学薄弱面发生破裂而产生[9],因此,层理缝的发育和分布受岩石本身的性质及结构等的控制。通过岩心、薄片观察及各类测试资料的分析,研究区长 7 页岩层系的层理缝受有机质含量、矿物组分、纹层结构等的影响,它们决定了岩石中层理的形态特征及分布规律,也影响着岩石的力学性质,是层理缝形成的基础。

3.1　砂岩层理缝主控因素

3.1.1　*矿物组分*

岩石矿物组成及分选性等对砂岩层理缝发育特征及发育程度具有重要影响。镜下观察发现当矿物成分成熟度较高时,在细砂岩内岩石颗粒粒径存在明显差异的部位容易发育层理缝,层理缝多沿岩性粒径变化界面延伸,延伸长度受到岩性变化界面延伸长度影响(图 6a)。受构造、气候、物源多种因素影响,研究区长 7 细砂岩内部黑云母矿物含量纵向上差异明显。当岩石分选好、云母以及黏土矿物含量多、呈层状分布时(图 2b)或云母、黏土矿物含量多但岩石分选差时(图 6c),层理缝发育,层理缝易沿云母以及黏土矿物颗粒边缘或解理发生破裂,并沿黏土矿物分布而呈现弯折、尖灭特征,且层理缝可沿层状云母延伸数厘米。砂岩内层理缝开度大,部分细砂岩内部受异常高压、云母以及黏土矿物含量影响,层理缝开度变化大,常被黑色有机质充填(图 6c);而粉砂岩分选性好,石英、黑云母以及黏土矿物矿物粒径较小,沿黑云母、或黑云母和黏土纹层发育的层理缝延伸长度短,开度小,连续性较差。

已有研究表明长 7 页岩层系胶结、压实等成岩作用强烈[57-58]。在砂岩内部,当颗粒分选好、呈线或凹凸接触(图 6d),或颗粒间胶结物含量较多时(图 6e),砂岩内部层理缝发育程度低。受岩石粒径影响,细粒及以上粒径砂岩形成层理缝大多呈现弯曲、分叉、尖灭等特征,在薄片下开度较大,易被有机质或沥青充填,层理缝裂缝壁上有明显有机质充填痕迹。而粉砂岩、泥质粉砂岩内部层理缝大多平直,延伸性较好,层理缝发育程度与黏土矿物含量及分选性有较大关系,薄片下观察发现,黏土矿物呈条带状分布部位,层理缝容易发育,而当黏土矿物含量少,矿物颗粒分布均匀时,层理缝基本不发育。

3.1.2　*纹层*

砂岩中控制层理缝发育的纹层类型包括黏土纹层、有机质纹层及黑云母纹层,不同类型纹层发育层理缝的密度存在显著差异(图 7)。黑云母纹层是砂岩中一类特殊且重要的纹层类型,纹层密度低但发育的层理缝密度高于另两类纹层。黑云母纹层与相邻纹层呈过渡接触或界限清晰的突变接触,形态普遍平直,层理缝可以沿薄纹层内部延伸,也可以发育在厚纹层的边界。在黑云母纹层构成的平行层理中,沿其展布的层理缝也呈水平板状平行分布,沿黑云母斜层理发育的层理缝则相应呈倾斜板状平行或交错分布。有机质纹层多以薄纹层形式夹于砂质纹层中,层理缝的横向延伸范围也受其控制。砂岩中的黏土纹层厚度较大,与相邻纹层界限清晰,纹层内部相对均质,因此,层理缝常常沿纹层边界发育,密度更低,且形态更不规则。

纹层密度对层理缝发育程度也具有显著影响。纹层数量决定了可供破裂的薄弱面数量,因此,在构造、异常压力等外部动力作用下,纹层密度越大的样品中层理缝的密度也往往更高(图 8),这与前人的认识存在一定差异[32-33]。地表露头与岩心观察发现,研究区细砂岩多呈块状特征,纹层不发育;

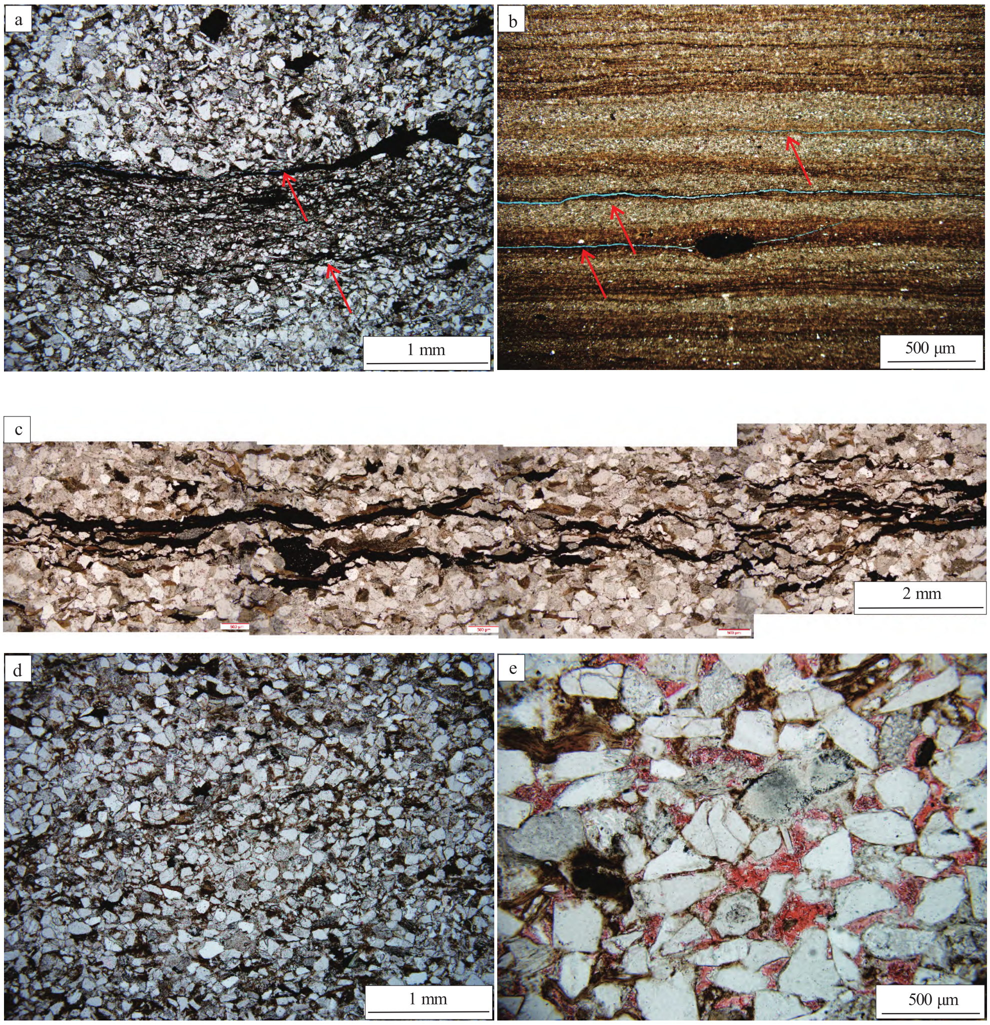

图 6 鄂尔多斯盆地西南部延长组长 7 页岩层系层理缝控制因素

a.细砂岩中沿矿物粒径变化界面发育的层理缝,A7 井,1 934.1 m;b.粉砂岩内层理缝,形态平直,A6 井,2 052.2 m;c.层理缝被黑色有机质充填,A1 井,2 364.9 m;d.压实作用强烈的细砂岩,A10 井,1 874.4 m;e.方解石胶结强烈的石英砂岩,A10 井,2 669 m。

Fig.6 Controlling factors of bedding-parallel lamellated fractures in Chang 7 shale system in southwestern Ordos Basin

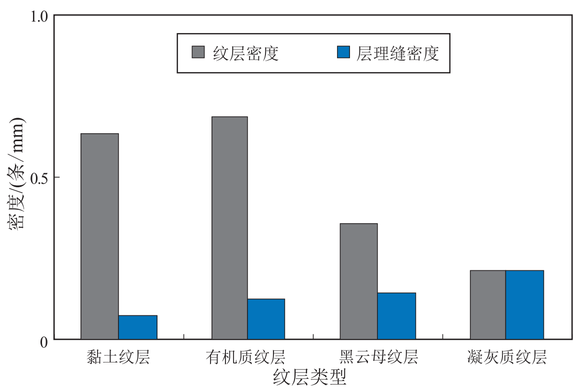

图 7 鄂尔多斯盆地西南部延长组长 7 页岩层系不同类型纹层的层理缝密度

Fig.7 Density of bedding-parallel lamellated fractures of different types of laminae in Chang 7 shale system in southwestern Ordos Basin

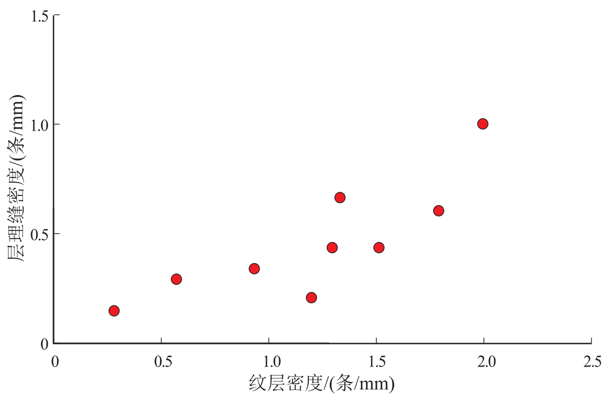

图 8 砂岩黏土纹层密度与相关层理缝密度的关系

Fig.8 Relationship between density of clay layers and density of related bedding-parallel lamellated fractures in sandstones

镜下统计表明,砂岩中纹层密度远低于泥页岩纹层密度,因而层理缝密度较泥页岩低。

纹层厚度是另一个影响因素,层理缝更易沿薄纹层发育。因此,在不同的岩相中,即使受同一种纹层控制,纹层厚度的差异也会导致层理缝密度的

差异(图 2d,h)。一方面,薄纹层代表了更高的纹层密度,间接影响层理缝的密度;另一方面,外力驱动的层理缝破裂与相邻纹层的弹塑性差异有关[35],较薄的纹层厚度反映沉积条件变化剧烈,导致其力学差异更大,从而促进了层理缝的发育。

3.2　页岩层理缝主控因素

3.2.1　有机质含量

有机质含量是页岩层理缝发育程度的重要影响因素。薄片下观察到,泥页岩未充填层理缝多沿暗色有机质条带延伸,随着暗色条带的增多,层理缝密度逐渐增加(图 2d,h)。在沉积过程中,由于沉积气候、物源、水动力差异以及湖盆氧化还原环境转化,会导致不同时间沉积下来的页岩有机质含量纵向上存在差异,有机质含量差异导致不同部位页岩岩石力学性质的差异。已有研究表明,有机质生烃增压产生的局部异常流体压力会导致页岩层沿着软弱面发生破裂,从而形成层理缝[6,59]。有机质含量差异导致页岩存在更多的岩石力学薄弱面,从而导致富有机质页岩更容易形成层理缝。

3.2.2　矿物组分

页岩油气储层页岩矿物成分以黏土矿物为主[60-62]。庆城—华池地区长 7 页岩层系主要发育半深湖—深湖和前三角洲亚相页岩,受盆地西北、东南方向等多物源供给,以及多期重力流沉积影响,不同岩相页岩脆性矿物含量变化大,如石英、长石等含量均变化较大[63-64]。根据脆性矿物含量不同,可将长 7 页岩分为 3 种类型,分别为:黏土质泥页岩、砂质泥页岩以及凝灰质泥页岩。受脆性矿物含量影响,不同性质页岩层理缝发育程度存在明显差异。黏土质泥页岩薄片下颜色多呈深褐色、黑褐色,颜色较深,有机质呈条带状分布且密度较大,石英、长石等脆性矿物含量少、粒径小,层理缝沿有机质条带破裂(图 2h)。砂质泥页岩中石英、长石颗粒含量多且变化大,局部可见细砂级石英颗粒,薄片下观察到薄片整体颜色较黏土质页岩薄片浅,呈棕褐色、浅褐色,有机质含量较低且呈明显带状分布,层理缝沿有机质富集条带破裂(图 6b),但层理缝密度低于黏土质泥页岩。此外,砂质泥页岩中,当砂岩呈透镜状分布、粒径较大时,常沿岩性变化界面或石英颗粒边缘破裂形成层理缝。凝灰质泥页岩主要为黑色页岩或凝灰质页岩。岩心及薄片显示,当凝灰质含量较高时,黏土与凝灰质呈条带状互层,因而层理缝极为发育(图 2i)。

3.2.3　纹层

控制页岩层理缝发育的纹层类型包括黏土纹层、有机质纹层和凝灰质纹层。在页理发育的页岩中,这些纹层以书页状互相叠置,沿这些纹层发育的层理缝也因此呈水平板状平行分布(图 2d)。而在页理较弱的粉砂质页岩中,层理缝形态更多为波状不平行分布(图 2h)。页岩中的黏土纹层极少发育层理缝(图 7)。有机质纹层是页岩中层理缝发育的主导纹层,作为非矿物的塑性组分,其与相邻的黏土、粉砂纹层力学性质差异较大,有利于层理的破裂成缝。与此同时,成岩过程中伴随有机质成熟发生的有机酸溶蚀作用,制造了沿纹层发育的溶蚀微裂缝,在生烃增压作用下这些微裂缝可以进一步扩展延伸、彼此连通,形成尺度更大的层理缝[9,12]。

页岩层理缝的密度同样受纹层密度控制。有机质纹层密度较低时,随着纹层密度增加,相关层理缝的密度逐渐增大,此时发育的层理缝密度可达 1.53 条/mm,最大约 8 条/mm。当纹层密度继续增大时,层理缝密度逐渐开始下降(图 9)。这一趋势与前人观察结果相似[32-33]。已有研究认为,在纹层密度较低时,随着纹层密度的增加,可供破裂的软弱面增多,层理缝更为发育;而过于密集的纹层意味着动荡富氧的古水体环境或陆源物质季节性注入,不利于有机质保存,进一步削弱了生烃增压作用,从而抑制了层理缝的发育[34]。然而,纹层的密集发育也增大了通过非破裂方式消耗应变能的可能,尤其对于塑性的有机质纹层而言,在外力作用下发生层间滑动,释放部分应力,也会抑制层理缝的产生[65]。

4　结论

(1)长 7 页岩层系中层理缝发育。砂岩层理缝大多顺黑云母层理面分布,连续性好,少部分被

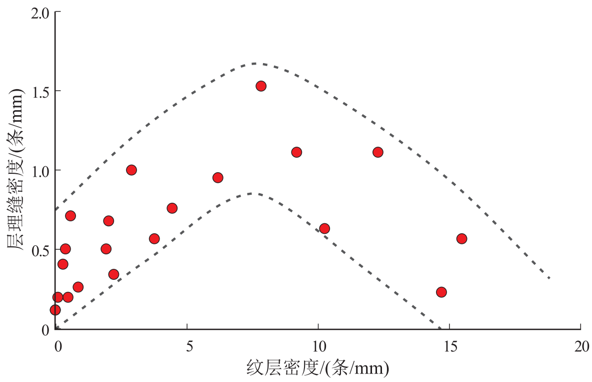

图 9　泥页岩有机质纹层密度与相关层理缝密度的关系

Fig.9　Relationship between density of organic matter layers and density of related bedding-parallel lamellated fractures in shale

有机质局部或完全充填。层理缝普遍未被充填,开度集中在 0~10 μm,密度集中在 0~0.6 条/mm。页岩层理缝发育在各类泥页岩及凝灰岩夹层中,大多沿着有机质纹层、凝灰质纹层构成的页理面分布,因此,较砂岩中更为密集。页岩层理缝大多未充填,少数被方解石、有机质局部或完全充填。页岩层理缝开度更小,约 98%的页岩层理缝介于 0~10 μm,但密度更大,在页理密集的黑色页岩和纹层发育的凝灰岩夹层中可达 1.4~2 条/mm。

(2)层理缝的发育程度受有机质含量、岩性、矿物组分、纹层结构等影响。砂岩层理缝主要受矿物组分、黑云母纹层控制,当砂岩分选好、黑云母含量多且呈层状分布时,层理缝发育程度高。砂岩中厚度较大的纹层中层理缝发育程度显著低于薄纹层,随着纹层密度增加,层理缝的发育程度随之增加。页岩层理缝主要发育在有机质纹层中,有机质含量越多,页理缝发育程度越高。凝灰质泥页岩层理缝发育程度最高,黏土质泥岩次之,砂质泥页岩层理缝发育程度最低。与砂岩不同,页岩层理缝密度随纹层密度先增加后降低。

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利益冲突声明/Conflict of Interests

所有作者声明不存在利益冲突。

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作者贡献/Authors' Contributions

卢晧完成实验操作和论文初稿撰写与修改;张皎生、李超提供实验素材并参与实验设计;曾联波、吕文雅参与实验指导、论文设计以及论文指导修改;刘艳祥参与论文修改;李睿琦参与数据整理与绘图。所有作者均阅读并同意最终稿件的提交。

LU Hao completed the experimental operation and the writing and revision of the paper. ZHANG Jiaosheng and LI Chao provided the experimental materials and participated in the experimental design. ZENG Lianbo and LÜ Wenya guided the experiment operation, paper design and revision. LIU Yanxiang participated in the paper revision. LI Ruiqi participated in the data collation and mapping. All authors have read the last version of the paper and consented to its submission.

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