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页岩孔隙—纹层缝的特征及分布模式研究 ——以济阳坳陷富有机质纹层状页岩为例

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摘要 【目的】孔隙—纹层缝系统是页岩油重要的储集空间和渗流通道,控制着页岩油的分布。由于孔隙和纹层缝在成因上的内在联系,因此将孔隙—纹层缝系统作为一个整体来进行研究。【方法】以济阳坳陷古近系沙三下一沙四上亚段页岩为例,从纹层尺度对两种典型岩相开展显微镜观察、扫描电镜和扫描电镜—能谱分析—自动矿物参数定量分析系统(SEM-EDS-AMICS)联用等一系列实验,探讨孔隙—纹层缝系统的特征。【结果】富有机质纹层状灰岩主要发育方解石连生孔(晶间孔、粒间孔、溶蚀孔),占总面孔率的32.48%,纹层界线清晰,纹层缝发育。富有机质纹层状泥岩以黏土矿物连生孔(晶间孔、片间孔、粒间孔)最为发育,占总面孔率的37.51%,同样发育良好的纹层缝。【结论】富有机质纹层状灰岩和富有机质纹层状泥岩的孔隙—纹层缝系统分别由方解石晶间孔—纹层缝系统和黏土矿物晶间孔—纹层缝系统组成。两种岩相孔隙—纹层缝系统的发育受沉积、成岩作用的控制,沉积环境控制着纹层的类型及组合方式;而在成岩过程中,富有机质纹层状灰岩主要受方解石重结晶作用和溶蚀作用的影响,富有机质纹层状泥岩则以黏土矿物转化和有机质的热演化作用影响为主。该研究明确了孔隙—纹层缝系统的分布模式及其发育控制因素,对指导济阳坳陷页岩油的勘探开发具有重要意义。

关键词 孔隙—纹层缝系统;岩相;陆相页岩;形成机制;页岩油

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0 引言

页岩油作为我国重要的非常规油气之一,其储层特征和分布规律一直是研究的热点(邹才能等, 2023)。陆相页岩储集空间包括孔隙和裂缝,孔隙的大小、形态以及裂缝的类型、分布等特征对页岩的储集性能有着重要影响,对页岩油开采至关重要(徐祖新等, 2016; Su *et al.*, 2023; 曹琰等, 2024; 丁文龙等, 2024; 王伟庆等, 2024)。受沉积环境影响,济阳坳陷沙三下一沙四上页岩纹层十分发育,不同纹层孔隙表现出极强的非均质性,形式多样的纹层类型及组

合有助于纹层缝的形成(陈世悦等, 2016)。纹层是组成页岩最基本的沉积单元结构(倪良田等, 2024),不同纹层因矿物组分、晶体结构、颗粒粒度等差异而存在纹层界面,受相邻纹层力学性质差异及界面处应力作用影响而在纹层界面发育的裂缝称为纹层缝(王超等, 2018; 蒲秀刚等, 2019; 赵贤正等, 2023; 施振生等, 2025; 吴科睿等, 2025)。纹层缝的存在对储层的水平渗流能力有重大影响,有利于油气的运移和富集(王勇等, 2017; Liu *et al.*, 2019; 徐效平, 2023)。

现有研究对页岩孔隙和纹层缝的类型、分布及

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成因已有一定认识(Lai *et al.*, 2022; Zhang *et al.*, 2024),但前人多将孔隙和纹层缝分别进行研究。实际上受沉积环境、岩相类型、成岩作用和有机质热演化作用等的综合影响,二者在成因上有一定的内在联系(Chen *et al.*, 2025)。不同岩相中纹层成分、结构、组合以及界面接触关系的差异影响孔隙和纹层缝的类型、形貌、尺度、分布等特征;在低渗透的页岩中,纹层缝是流体运移的重要通道,在运移过程中会发生流体—岩石相互作用,促进周围基质中孔隙的产生,形成了与纹层缝相连的孔隙网络;同时纹层界面处的孔隙也会产生应力集中,进而诱导纹层缝的发育和扩展(Chen *et al.*, 2025)。纹层缝和孔隙相互连通,共同影响流体的赋存与流动,构成孔隙—纹层缝系统。

本文以济阳坳陷沙三下一沙四上富有机质纹层状灰岩和富有机质纹层状泥岩两种典型岩相为例,从纹层尺度对孔隙和纹层缝进行定量化表征,探讨孔隙—纹层缝系统的分布模式及其发育控制因素,这将有利于了解和认识页岩油的运移、富集等特性,也对页岩油的勘探开发奠定重要的理论和实践基础。

1 地质背景

济阳坳陷位于渤海湾盆地东南部,是渤海湾盆地的次级构造单元之一(图 1a),总面积约为 $2.65\times 10^4\text{ km}^2$ 。坳陷东部为垦东—青坨子凸起,西部和北部为埕宁隆起,南部为鲁西隆起,内部发育东营凹陷、惠民凹陷、沾化凹陷、车镇凹陷四个凹陷带(Wang *et al.*, 2018; Ma *et al.*, 2023; Xiong *et al.*, 2024),表现为“多凸多凹、凹凸相间”的构造格局(图 1b)。

济阳坳陷的新生界地层十分发育,自上而下依次发育古近系、新近系和第四系(图 1c)。其中,古近系沙河街组地层分布最为广泛,可进一步划分为沙四段、沙三段、沙二段和沙一段。在沙三下一沙四上亚段($E_3^x-E_4^s$)时期,湖盆面积不断扩张,气候暖湿,水体深度不断增大,形成半深湖—深湖环境,页岩沉积厚度大,纹层发育(吴靖等, 2017)。岩相以富有机质纹层状灰岩和富有机质纹层状泥岩最为典型,分布最为广泛(孙焕泉, 2017; 杨勇, 2023)。

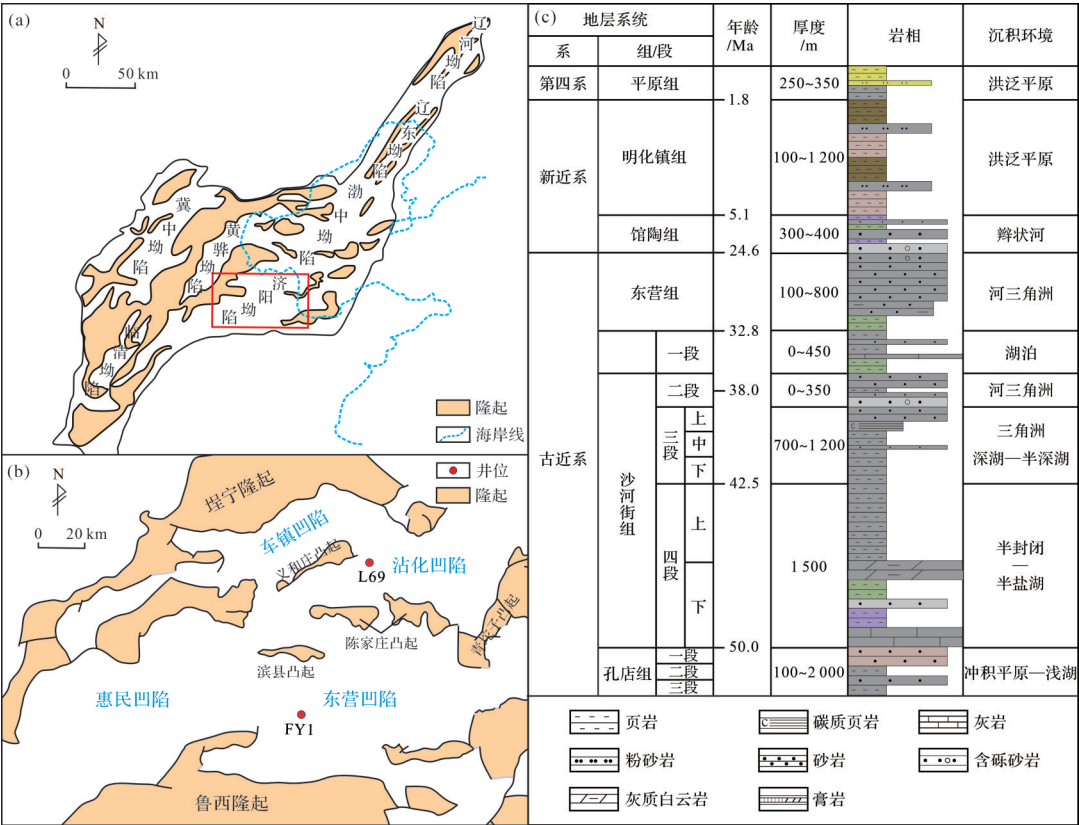


图 1 济阳坳陷区域位置及综合柱状图(据 Ma *et al.*, 2023; Xiong *et al.*, 2024 修改)

Fig. 1 Regional map and comprehensive stratigraphic column of the Jiyang Depression (modified from Ma *et al.*, 2023; Xiong *et al.*, 2024)

2 实验样品与实验方法

2.1 实验样品

选取济阳坳陷沙三下一沙四上共43块泥页岩样品,对样品进行总有机碳(TOC)和热解分析,并开展显微镜和扫描电镜观察,从中选取19块样品进行自动矿物参数定量分析系统(AMICS)矿物扫描识别,富有机质纹层状灰岩和富有机质纹层状泥岩是研究区发育广泛的“甜点”岩相,因此选取这两种典型岩相(共3块样品)对孔隙—纹层缝系统进行分析(表1)。

2.2 实验方法

有机碳分析采用CS-744碳硫分析仪完成。称取150 mg研磨至200目的粉末样品置于陶瓷坩埚中,少量多次滴入浓度5%的稀盐酸酸化,以充分去除无机碳,待无气泡产生后,用蒸馏水冲洗10~15次后置于60℃烘箱中12 h,最后加入铁和钨后放置在坩埚基座上,开始测试。

岩石热解分析使用Rock-Eval 7岩石热解仪完成。称取40 mg研磨至200目的粉末样品置于坩埚中,将坩埚放入热解分析仪,以25℃/min的升温速率加热至300℃,停留5 min测得 S_1 (游离烃含量),继续升至1 600℃测得 S_2 (裂解烃含量), S_2 峰对应的最高温度即为 T_{max} (最高热解峰温)。

对所选取样品进行光学显微镜观察和场发射扫描电镜观察,分别从微、纳米尺度对岩石的孔缝发育特征及规律进行描述。实验所用的扫描电子显微镜(SEM),最高分辨率可达0.9 nm(金颗粒标样),最大放大倍率为40万倍。

通过SEM-EDS-AMICS分析技术联用,对样品的典型区域进行动态扫描,AMICS能够依据矿物不同灰度的背散射图像自动采集能谱数据,将采集到的信息与标准数据库中的矿物信息进行自动匹配,从而得到样品的矿物成分,对于未自动识别的能谱数据,在数据处理时通过建立新的矿物标准,与标准矿物数据库中的矿物进行比匹配,以确定其矿物种类。

利用AMICS得到的处理数据,导出样品的矿物成分、矿物连生关系等信息,对其储集空间分布特征进行分析。实验所用的AMICS,扫描分辨率可达20 nm,配备超过2 000种标准矿物的标准矿物数据库,可开展大面积、全矿物、高分辨率的定量矿物自动分析,快速、准确地测定样品的物质组成、成分特征、矿物嵌布特征、矿物粒级分布、矿物解离度、矿物连生关系等结果。本研究所统计的孔隙包括实际的孔隙及充填在孔隙内部的部分有机质、沥青等。所有实验分析均在中国石油大学(华东)深层油气国家重点实验室完成。

3 结果

富有机质纹层状灰岩和富有机质纹层状泥岩在纹层组合上存在差异(图2),其储集空间也不同。

3.1 富有机质纹层状灰岩:方解石纹层与黏土纹层

富有机质纹层状灰岩主要由亮晶方解石纹层和富有机质黏土纹层组成(图2a),孔隙类型主要为晶间孔,存在部分溶蚀孔隙,粒间孔和有机孔发育较少(图3)。纹层缝和层内微裂缝发育,与孔隙共同形成良好的储集空间。

根据孔隙—矿物赋存方式差异,将与某种矿物直接接触的多种类型的孔隙统称为连生孔,如方解石连生孔包括方解石晶间孔、方解石溶蚀孔以及方解石与其他矿物颗粒之间的粒间孔。由实验结果可知,富有机质纹层状灰岩以方解石连生孔最为发育,占总面孔率的32.48%(图4a),其次为黏土矿物连生孔,占总面孔率的17.02%(图4a)。该岩相中,以晶间孔发育的方解石纹层总面孔率高,最高可达8.51%,纹层界面处也有着较高的面孔率(图5)。

3.1.1 亮晶方解石纹层

亮晶方解石纹层主要发育方解石晶间孔(图3a),孔隙边缘光滑,孔径分布范围广,最小仅有23 nm,最大可达80 μm ,方解石晶形完整,晶体接触边缘可形成方解石晶间缝,开度介于16~159 nm;受

表1 济阳坳陷两种典型岩相样品信息

Table 1 Data for two typical lithofacies samples from the Jiyang Depression

样品 编号	矿物成分/%							岩相	TOC/%	S_1+S_2 /(mg/g)	T_{max} /℃
	斜长石	正长石	石英	白云石	方解石	黏土矿物	其他矿物				
L-1	9.86	0.17	11.29	3.46	48.31	19.77	2.79	富有机质纹层状灰岩	1.68	7.33	450
L-2	4.66	0.12	5.09	5.62	69.86	7.97	2.29	富有机质纹层状灰岩	2.66	23	445
FY-1	9.51	1.44	22.01	7.66	7.97	42.57	3.82	富有机质纹层状泥岩	2.48	21.63	443

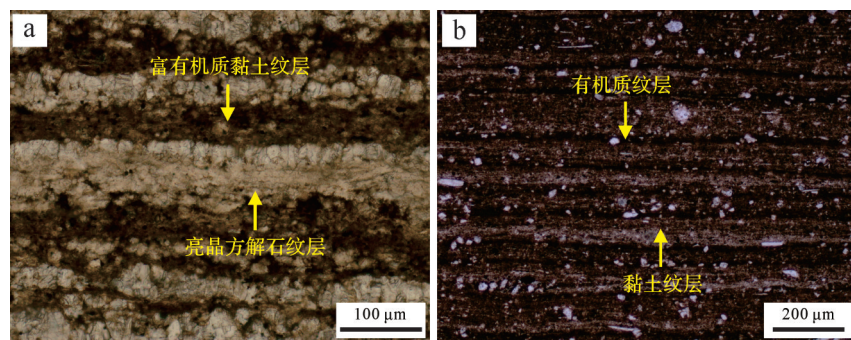


图2 富有机质纹层状灰岩和富有机质纹层状泥岩的纹层组合类型及特征

(a)富有机质纹层状灰岩,由亮晶方解石纹层和富有机质黏土纹层组成,L69井,3 047.02 m;(b)富有机质纹层状泥岩,由有机质纹层和黏土纹层组成,FY1井,3 209.42 m

Fig. 2 Characteristics of lamina assemblages of organic-rich rocks

(a) laminated sparry limestone composed of sparry calcite and clay laminae, well L69, 3 047.02 m; (b) laminated mudstone composed of organic and clay laminae, well FY1, 3 209.42 m

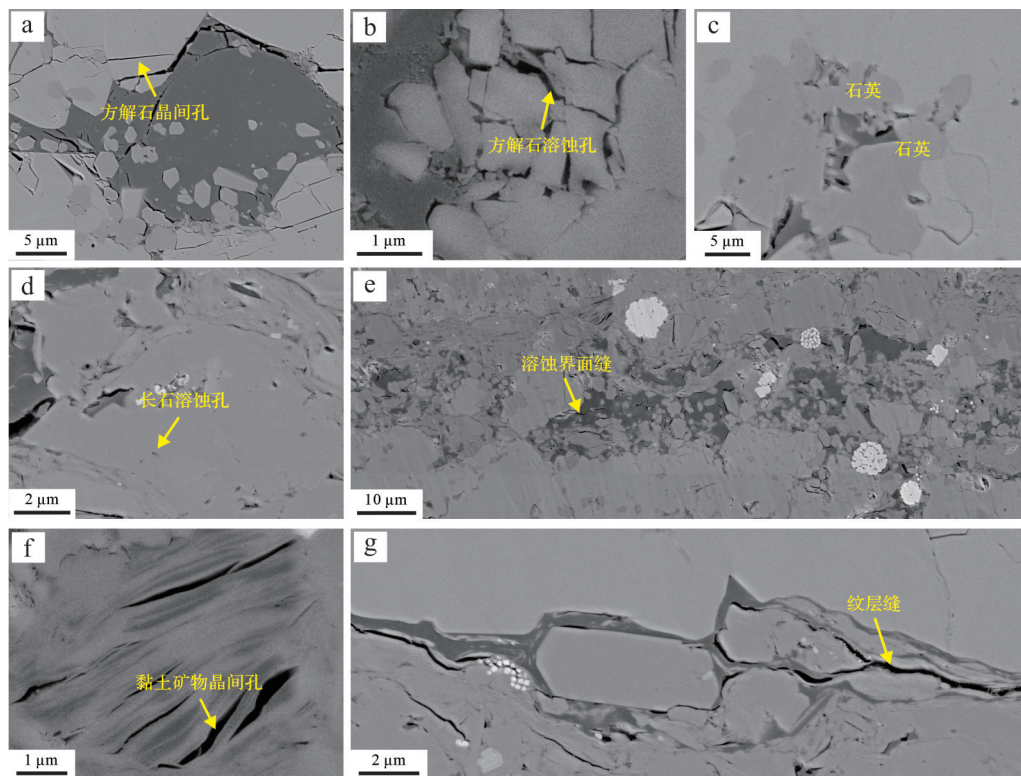


图3 济阳坳陷富有机质纹层状灰岩主要孔缝类型(L69井,3 047.02 m)

(a)方解石晶间孔;(b)方解石溶蚀孔;(c)石英晶间孔;(d)长石溶蚀孔;(e)受有机酸侵蚀作用形成的方解石溶蚀缝;(f)黏土矿物晶间孔;(g)方解石纹层与有机黏土纹层界面形成清晰纹层缝

Fig. 3 Main pore-fracture types of organic-rich laminated limestone in Jiyang Depression (well L69, 3 047.02 m)

(a) calcite intercrystalline pores; (b) calcite dissolution pores; (c) quartz intercrystalline pores; (d) feldspar dissolution pores; (e) calcite dissolution fractures due to organic acid erosion; (f) clay mineral intercrystalline pores; (g) laminar fractures at interface of calcite and clay laminae

溶蚀作用影响发育大量方解石溶蚀孔(图3b),孔径一般介于20 nm~2.32 μm,形成溶蚀界面(图3e)。在溶蚀界面处,微晶石英发育,因此发育大量石英晶间孔(图3c),孔径一般介于100 nm~5 μm,长石溶蚀孔在该界面也有较多发育(图3d),孔径通常在100 nm

以下,孔隙形态多为港湾状、蜂窝状等不规则形状,孔隙常呈团块状富集,有一定的连通性。方解石晶间孔周围可见交代作用而成的黄铁矿,黄铁矿形态多为块状,发育棱角分明的黄铁矿晶间孔。在方解石晶体颗粒接触边缘可见方解石晶间缝,而在溶蚀

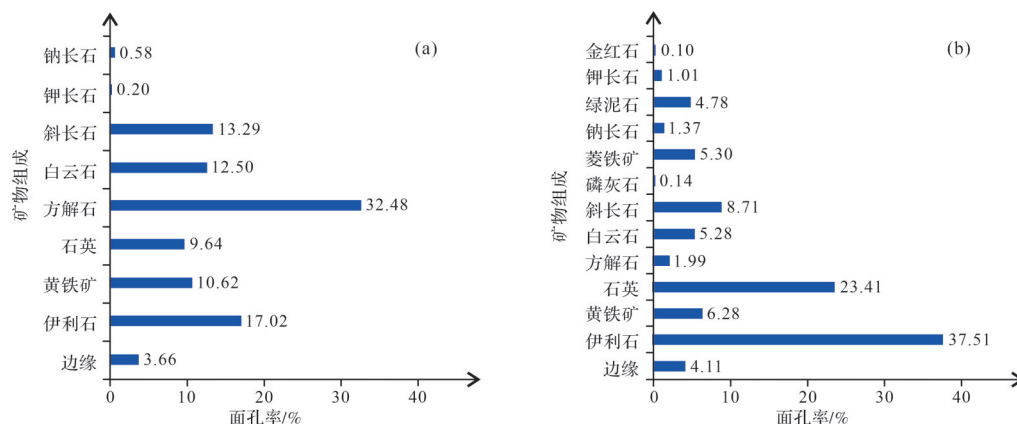


图4 不同岩相富含有机质纹层矿物与孔隙连生关系

(a)富含有机质纹层状灰岩;(b)富含有机质纹层状泥岩

Fig. 4 Relationships between minerals and pores in organic-rich laminae of different lithofacies

(a) organic-rich laminated limestone; (b) organic-rich laminated mudstone

界面处往往有溶蚀型裂缝的发育,裂缝发育相对孤立且开度较小,连通性较差。

该纹层中,方解石连生孔最为发育,占该纹层总面孔率的50%以上,最高可达58.55%(图5);其次为石英连生孔和长石连生孔,当发生溶蚀现象时,纹层中石英连生孔的占比有明显增大,通常在35%以上,最高可达44.43%(图5),而在未发生溶蚀的方解石纹层中,石英连生孔在10%左右,最少仅为5.4%(图5),白云石连生孔占比则随溶蚀作用的发生而降低,最低仅占0.97%(图5)。黄铁矿连生孔相对较少,通常在10%以下,当黄铁矿与方解石发生交代作用时,黄铁矿连生孔占比显著增加,最高可达22.86%(图5)。

3.1.2 富含有机质黏土纹层

富有机质黏土纹层中顺层展布的黏土矿物含量高,形成大量黏土矿物晶/片间孔,孔径范围较小,通常介于13~259 nm,由于缺乏碎屑颗粒的支撑,孔隙形态多呈现为明显的狭缝状、纤维状及片状(图3f)。该纹层中发育较多石英、长石等碎屑颗粒,与周围分布的黏土矿物构成粒间孔。白云石晶间孔形态多为圆形或椭圆形,孔径通常小于2 μm。纹层中发育草莓状黄铁矿,形成的黄铁矿晶间孔多为纳米级孔隙,一般介于53~284 nm,聚集的形态使孔隙间具有较好的连通性。

该纹层中,黏土矿物连生孔的占比最高可达63.34%,其次为长英质矿物连生孔,长石连生孔的占比均在10%以上,石英连生孔的占比多大于7%(图5)。白云石的大量发育使白云石连生孔占比高于方

解石纹层,白云石连生孔占比变化范围较小,黄铁矿连生孔较少,通常介于3%~10%(图5)。

3.1.3 纹层界面

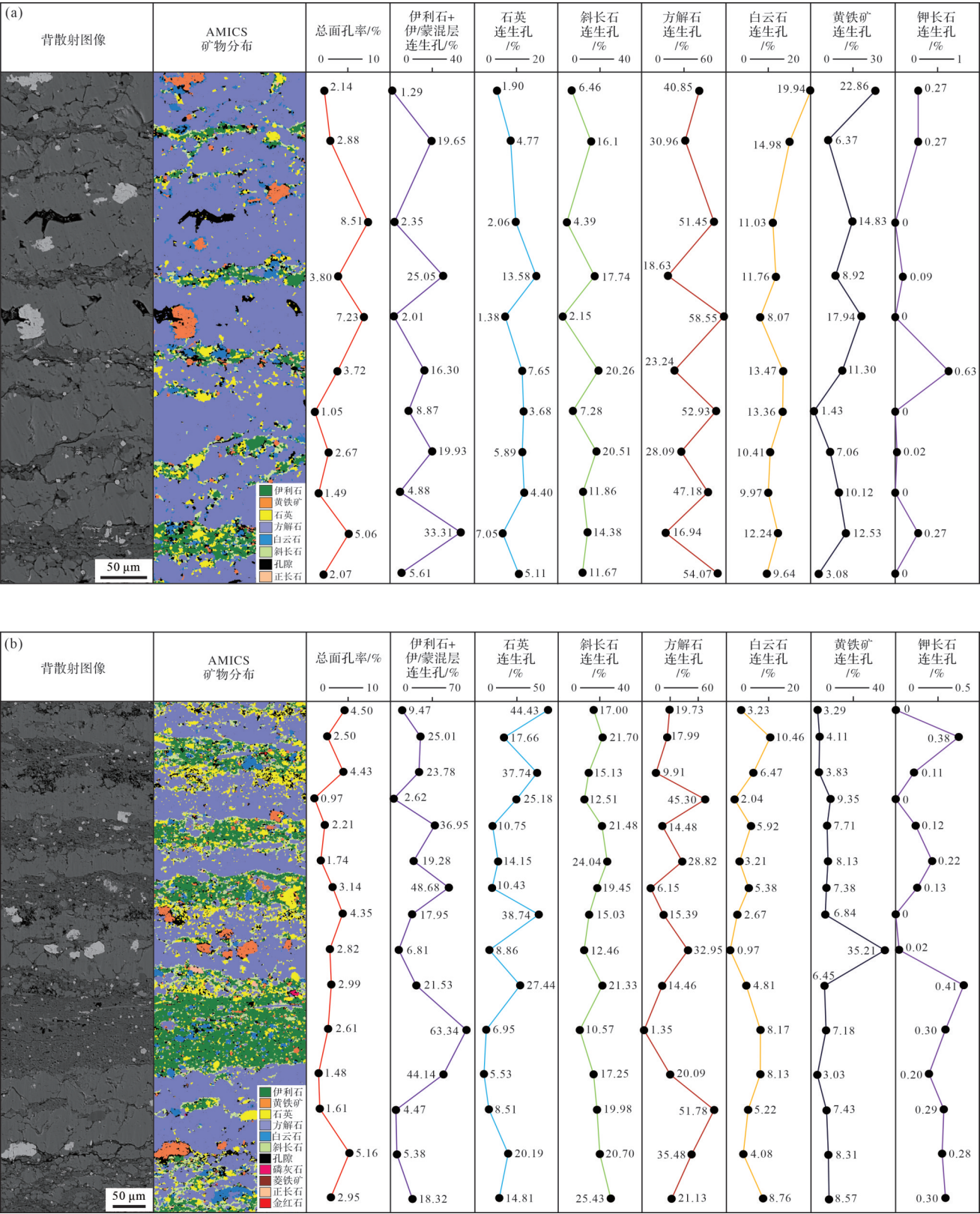
在纹层交界处,除方解石和黏土矿物这两类主要矿物外,微晶石英和草莓状黄铁矿也有较多发育,因此石英连生孔和黄铁矿连生孔发育较多。脆性的方解石和塑性的黏土矿物相互接触形成突变界面,发育良好的纹层缝(图3g),受矿物脆性差异影响裂缝开度较大,结构形态较为简单,一般为平直或曲折的层状,走向接近水平,延伸较远,裂缝相互交错,彼此之间连通性强,其内部常有矿物充填,如方解石、石英、沥青等。延伸的纹层缝与周围发育的各类孔隙相互贯穿连通,共同构成了孔隙—纹层缝系统。

3.2 富有机质纹层状泥岩:黏土纹层与有机质纹层

富有机质纹层状泥岩主要由黏土纹层和有机质纹层组成(图2b),主要孔隙类型为粒间孔、晶间孔,其次为溶蚀孔隙和有机质收缩孔(图6)。裂缝类型也较为多样,纹层缝发育良好(图6)。在各类孔隙中,以黏土矿物连生孔最为发育,占总面孔率的37.51%(图4b),其次为石英连生孔,占23.41%(图4b),长石连生孔和黄铁矿连生孔也有较多发育。

3.2.1 黏土纹层

黏土纹层中以黏土矿物晶(粒)间孔和长英质矿物粒间孔为主(图6a~c),长石溶孔、碳酸盐矿物晶间孔、黄铁矿晶间孔、菱铁矿晶间孔、有机质收缩孔等(图6d~g,i)也有发育。黏土矿物晶间孔形态多呈片



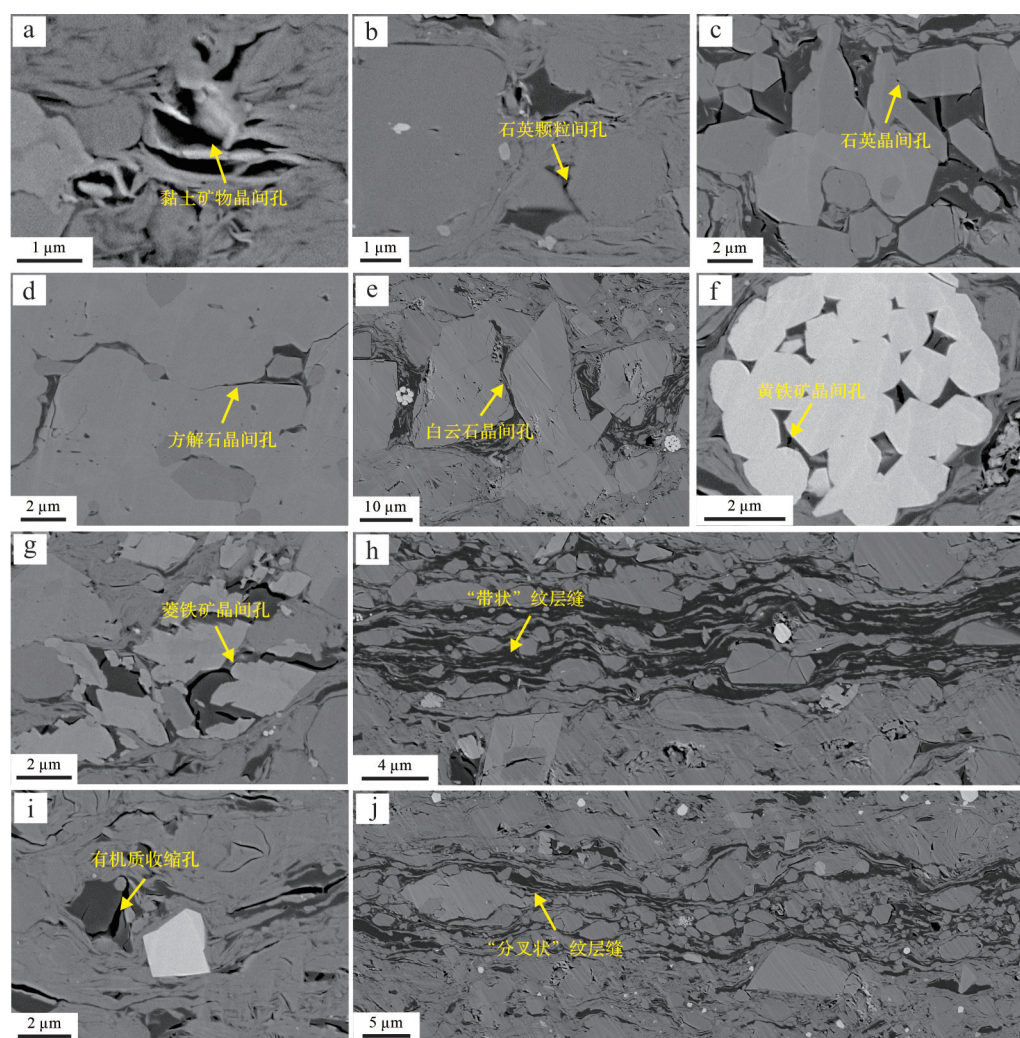


图6 济阳坳陷富有机质纹层状泥岩中主要孔缝类型(FY1井, 3 209.42 m)

(a)黏土矿物晶间孔;(b)石英颗粒间孔;(c)石英晶间孔;(d)方解石晶间孔;(e)白云石晶间孔;(f)黄铁矿晶间孔;(g)菱铁矿晶间孔;(h)黏土纹层与有机质纹层交界处“带状”纹层缝;(i)有机质收缩孔;(j)黏土纹层与有机质纹层交界处“分叉状”纹层缝

Fig. 6 Main pore-fracture types of organic-rich laminated mudstone in Jiyang Depression (well FY1, 3 209.42 m)

(a) clay mineral intercrystalline pores; (b) quartz intergranular pores; (c) quartz intercrystalline pores; (d) calcite intercrystalline pores; (e) dolomite intercrystalline pores; (f) pyrite intercrystalline pores; (g) siderite intercrystalline pores; (h) 'banded' laminar fractures formed at clay/organic laminae interface; (i) organic matter shrinkage pores; (j) 'bifurcated' laminar fractures formed at clay/organic laminae interface

状,开度介于15~398 nm,长轴可达几微米(图6a)。纹层内发育大量石英、长石等碎屑颗粒,当基质黏土矿物与脆性长英质矿物相接触时,由于二者的脆性差异,分布在长英质矿物颗粒周围的黏土矿物常发生变形,形成新月形孔隙及黏土矿物收缩缝,孔隙边缘较为平滑。黄铁矿多生长在黏土矿物和长英质矿物之间,主要以草莓状集合体的形式分散产出,晶形完好。在一个黄铁矿集合体中,各晶体之间常形成多个不规则多边形孔隙,孔隙内部常被泥质或有机质充填,孔径较小,一般介于35 nm~1.14 μm(图6f)。有机质收缩孔形态多样,多呈不规则状和圆形,孔径

通常在微米级以下(图6i)。

如图7所示,该纹层面孔率相对较小,一般介于3.15%~4.28%。黏土矿物连生孔最多,最多可达59.42%,其次为石英连生孔和长石连生孔,石英连生孔多超过10%,最高可达34.72%,而长石连生孔发育则相对较少。黄铁矿连生孔的含量也较高,占总面孔率的2.64%~18.43%,多分布在纹层界面边缘。

3.2.2 有机质纹层

有机质纹层中矿物种类多样,形成的储集空间类型也具有多样性。纹层内发育大量有机孔和黏土矿物晶间孔(图6a, i),其次为石英晶间孔(图

6c),多分布在纹层界面边缘,孔径较小。此外白云石、黄铁矿、菱铁矿等矿物晶间孔也均有发育(图6e~g)。

有机质纹层面孔率主要介于5.58%~6.90%,明显高于黏土纹层(图7)。在该纹层中,发育大量的微晶石英、白云石、黄铁矿、菱铁矿等矿物,其中以微晶石英最为发育,石英连生孔的占比明显多于黏土纹层,最高可占总面孔率的34.72%(图7)。黄铁矿和菱铁矿连生孔也有较好的发育,黄铁矿连生孔占比3.11%~10.61%,菱铁矿连生孔可占总面孔率的2.98%~11.35%,方解石和白云石连生孔占比较少,其中方解石连生孔大多低于2%(图7)。

3.2.3 纹层界面

黏土纹层和有机质纹层界面处常发育大量的纹层缝,缝内常被有机质、沥青等充填,纹层缝与周围片状的黏土矿物晶间孔/缝相互连通,形成“带状”分布的孔隙—纹层缝系统(图6h),当纹层缝中充填石英、方解石等晶体时,其相关孔隙也会与纹层缝连通,在晶粒边缘处,多形成“分叉状”的孔隙—纹层缝系统(图6j)。

4 讨论

页岩油储层孔隙—纹层缝系统由复杂的孔隙网络与纹层缝体系组合而成,具有类型复杂、形貌多

样、尺度不一、非均质性强等特征(何文渊,2022;吴科睿等,2025)。孔隙和纹层缝是页岩储层的重要组成部分,是良好的储集空间和渗流通道。孔隙—纹层缝系统的形成有利于页岩油的长距离运移,对提高页岩储层的渗透性具有重要意义,能够有效提高油气产能(金之钧等,2021)。

4.1 孔隙—纹层缝系统的发育控制因素

页岩的形成经历了沉积—成岩作用等一系列复杂的演化过程,其孔缝系统的发育规律受到不同阶段的多种因素控制(余志云等,2022;孙龙德等,2023)。

4.1.1 沉积作用

岩相受沉积环境的控制,不同岩相的成分、结构以及构造差异较大,进而影响孔缝的类型和分布方式(张顺等,2016)。沙三下—沙四上页岩主要发育在安静缺氧的深水环境,较高的湖水盐度易于湖水分层,形成纹层状的沉积构造(张建国等,2021)。受控于湖盆水体、物质供给、营养成分的变化,富有机质纹层状灰岩和富有机质纹层状泥岩具有不同的纹层组合样式(杨万芹等,2018;操应长等,2023;Liang *et al.*, 2023)。在暖湿的春夏季节,浮游生物的大量繁殖通过光合作用改变了水体的pH值,以生物化学方式促进了方解石的沉淀,形成方解石纹层;秋冬季节生物死亡导致水体缺氧,有机质保存,缺乏生物作

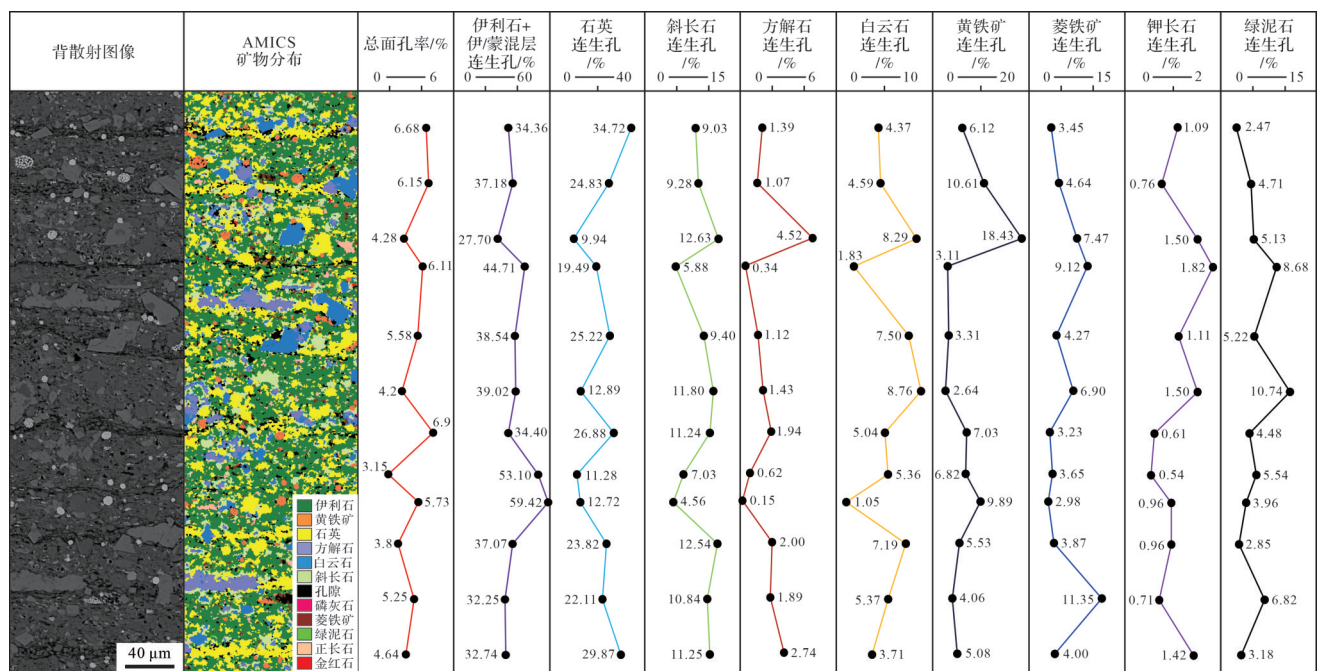


图7 富有机质纹层状泥岩中连生孔分布情况

Fig. 7 Distribution of associated pores in organic-rich laminated mudstone

用导致碳酸盐沉淀减少,形成富有机质黏土纹层(Liang *et al.*, 2023)。富有机质纹层状灰岩形成方解石纹层和黏土纹层互层,二者呈突变接触,纹层界线明显。同时刚性的方解石晶体起到支撑纹层结构的作用,使方解石纹层与黏土纹层之间成为潜在纹层缝(张顺等, 2015),再因二者力学性质的差异,纹层交界处为一个力学薄弱面,从而易于形成纹层缝(Xiong *et al.*, 2022)。当水体中碳酸盐饱和度不足时,难以达到方解石沉淀的条件,在生物繁盛的夏季,浮游藻类和细菌大量繁殖,有机质输入增加,形成富有机质纹层,而冬季的低温缺氧环境则有利于黏土纹层的保存(Liang *et al.*, 2023)。富有机质纹层状泥岩发育黏土纹层和有机质纹层,纹层界线较为模糊,以黏土矿物连生孔最为发育(图4)。受陆源输入影响,黏土纹层内分布有较多石英、长石等刚性颗粒,具有一定的抗压实性,对孔隙的发育和保存起着至关重要的作用(Macquaker *et al.*, 2014; Wang *et al.*, 2023),因此两类岩相中均发育较多的石英连生孔和长石连生孔(图4)。

4.1.2 成岩作用

成岩作用是在沉积基础上的进一步演化和改造,也对孔隙—纹层缝系统的发育和分布起到重要作用。随着埋深的增加,页岩储层受到压实作用的影响,造成原生孔隙降低,储集性变差(董春梅等, 2015; Milliken *et al.*, 2020; Zhang *et al.*, 2021)。但在压实过程中,片状的黏土矿物容易发生定向排列,从而形成力学薄弱面,有利于层间孔隙和纹层缝的形成(Ingram, 1953; Li *et al.*, 2022)。此外,不规则形状的刚性颗粒在一定程度上也会限制埋藏和压实过程中的孔隙塌陷,从而保留一定的原生孔隙(Huang *et al.*, 2023)。

富有机质纹层状灰岩的孔隙—纹层缝系统主要受方解石重结晶和溶蚀作用的影响。干酪根在热演化过程中释放的有机酸可显著影响方解石的演化过程:一方面,有机酸的存在可促进方解石的溶解与再沉淀,重结晶形成大颗粒方解石晶体,有利于晶间孔的发育(图5);另一方面,在有机酸流体的侵入作用下,方解石发生溶蚀作用而改善次生孔隙(Xin *et al.*, 2022; 徐效平, 2023),形成的大量溶蚀孔隙和溶蚀缝组成溶蚀界面(图3e),对孔隙—纹层缝系统产生积极影响。在这些溶蚀孔内,常见自生石英的充填(杜玉山等, 2024; Rao *et al.*, 2024),因此溶蚀界面处,石

英连生孔的含量也较高(图5)。方解石的重结晶作用和溶蚀作用使亮晶方解石纹层中的孔隙发育更具大孔优势(黎茂稳等, 2020),是富有机质纹层状灰岩的重要储集空间。

富有机质纹层状泥岩由黏土纹层和有机质纹层组成,在该岩相中,以黏土矿物转化和有机质热演化作用为主。黏土矿物的转化和有机质的生烃增压能够促进孔隙和微裂缝的发育(王森等, 2020; 陈扬等, 2022; Wang *et al.*, 2023),微裂缝包括纹层缝、异常压力缝和成岩缝(赵贤正等, 2023),大量黏土矿物脱水收缩,在降低自生骨架体积空间的同时,伴生的自生矿物晶间孔和收缩作用产生的成岩收缩缝能够有效提高储集空间(张顺, 2018; Milliken *et al.*, 2020; Xiong *et al.*, 2022)。在有机质热演化过程中,有机质生烃增压造成页岩储层破裂而产生异常压力缝,生烃释放后体积收缩,在有机质内部产生大量的有机孔(梁超等, 2017)。黏土纹层与有机质层的纹层界面为力学薄弱面,形成了许多“带状”纹层缝。大量发育的纹层缝沟通了彼此孤立的孔隙,与周围的有机孔和无机孔构成优势的孔隙—纹层缝系统,有利于页岩油气的储集和运移。

4.2 孔隙—纹层缝系统的分布模式

济阳拗陷从盆地边缘到洼陷中心岩相大致呈环带状分布,自南部缓坡带到北部深洼带,依次发育砂岩—一块状粉砂质泥岩—层状泥页岩相—纹层状灰岩相—纹层状泥岩相(图8a)。埋藏成岩阶段,热演化程度逐渐增高,地层压力系数普遍较大,富有机质纹层状灰岩和富有机质纹层状泥岩形成了类型多样的储集空间,孔隙—纹层缝系统发育(刘惠民等, 2019)。由亮晶方解石纹层和富有机质黏土纹层组成的富有机质纹层状灰岩以方解石晶间孔最为发育,其次为黏土矿物晶间孔,纹层缝延伸较远(图8b)。富有机质纹层状泥岩的黏土纹层以黏土矿物晶间孔和石英粒间孔最为发育,有机质纹层中则主要发育有机孔,纹层界线较为模糊,易发育多条平行纹层缝(图8c)。

5 结论

(1) 济阳拗陷沙三下—沙四上页岩以富有机质纹层状灰岩和富有机质纹层状泥岩最为典型。富有机质纹层状灰岩由亮晶方解石纹层和富有机质黏土纹层组成,以方解石连生孔最为发育,其次

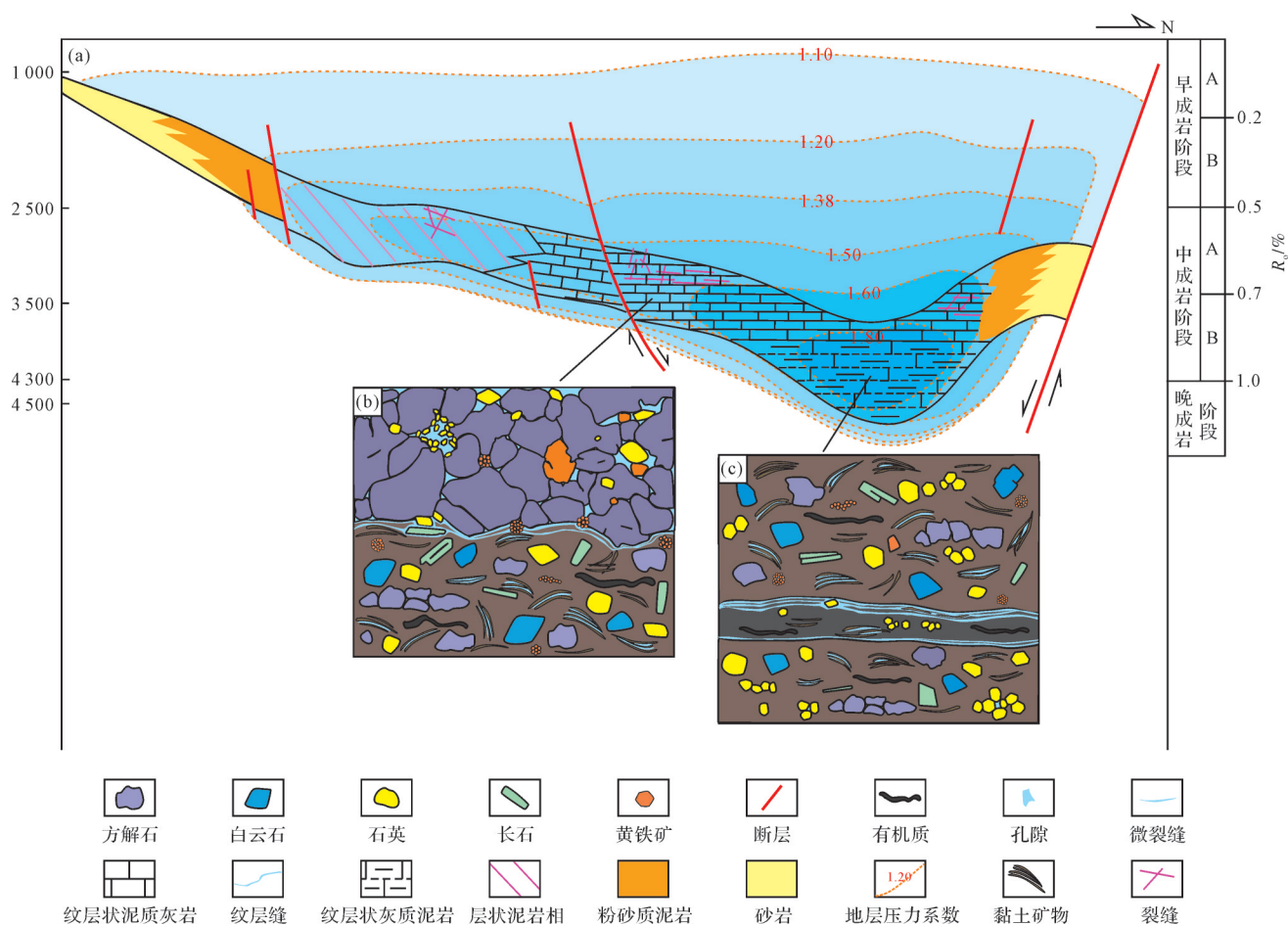


图8 济阳坳陷两种典型岩相孔隙—纹层缝系统分布示意图(据刘惠民等, 2019 修改)

(a) 储集相带分布模式; (b) 富有机质纹层状灰岩孔隙—纹层缝系统分布模式; (c) 富有机质纹层状泥岩孔隙—纹层缝系统分布模式

Fig. 8 Distribution map of pore-laminar fractures in two typical lithofacies of the Jiyang Depression (modified from Liu *et al.*, 2019)
(a) distribution pattern of reservoir facies; (b) distribution pattern of pore-laminar fracture system in organic-rich laminated limestone; (c) distribution pattern of pore-laminar fracture system in organic-rich laminated mudstone

为黏土矿物连生孔, 分别占总面孔率的 32.48% 和 17.02%, 该岩相中纹层界线清晰, 纹层缝延伸较远, 孔隙—纹层缝结构形态较为简单; 富有机质纹层状泥岩以黏土矿物连生孔最为发育, 占总面孔率的 37.51%, 纹层界线相对模糊, 易发育多条平行纹层缝。

(2) 研究区孔隙—纹层缝系统的发育分布受沉积—成岩作用的控制, 沉积过程控制了不同的矿物组成和纹层组合, 从而形成不同类型的孔隙—纹层缝系统; 而在成岩过程中, 除压实作用外, 富有机质纹层状灰岩的孔隙—纹层缝系统主要受方解石重结晶作用和溶蚀作用的影响, 而富有机质纹层状泥岩的孔隙—纹层缝系统则以黏土矿物转化和有机质的热演化作用为主。

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Characteristics and Distribution Patterns of Pore-Laminar Fractures of Shales: Case study of the organic-rich laminated shale in the Jiyang Depression

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Abstract: [Objective] Pore-laminar fracture systems are important reservoir spaces and seepage channels for shale

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oil, since they control the distribution of the oil. Most previous studies have discussed pores and laminar fractures separately but, in fact, they are closely related genetically. This study considers the pore-laminar fracture system as a whole. **[Methods]** The shale of the Paleogene Es_3^x - Es_4^s in the Jiyang Depression was selected as an example, and a series of experiments was carried out to investigate each of the laminae as a unit. Two typical lithofacies of organic-rich laminated limestone and organic-rich laminated mudstone were studied by microscope observation, scanning electron microscope (SEM) and SEM-EDS-AMICS analysis. The development, distribution mode and influencing factors of the pore-lamellar fracture system are discussed. **[Results]** It was found that the organic-rich laminated limestone has mainly developed intercrystalline, intergranular and dissolved calcite-associated pores, accounting for 32.48% of the total porosity area, followed by 17.02% due to intercrystalline and intergranular pores in clay minerals. The boundary between the limestone and mudstone laminae is clear, and both have well-developed laminar fractures. In the sparry calcite laminae, calcite-associated pores are dominant (up to 56.86%); in the clay laminae, clay-mineral-associated pores dominate (up to 46.69%). The organic-rich laminated mudstone contains mostly clay-mineral-associated pores, accounting for 37.51% of the total pore area. In the clay laminae, clay-mineral-associated pores account for up to 59.42% of the total pore area. In the organic laminae, the percentage of quartz-associated pores is significantly higher than in the clay laminae, accounting for up to 34.72% of the total pore area. The boundary between these two laminae is relatively vague, and laminar fractures are also highly developed. **[Conclusions]** The pore-laminar fracture system of organic-rich laminated limestone is mainly composed of calcite intercrystalline pores, clay mineral intercrystalline pores and laminar fractures. The organic-rich laminated mudstone is mainly composed of clay mineral intercrystalline pores, organic pores and laminar fractures. The development of different pore-laminar fracture systems in the two lithofacies is controlled by sedimentation and diagenesis. The depositional environment has influenced lithofacies development. Their composition, structure and tectonic histories vary greatly, affecting the type and distribution of pores and fractures. Diagenesis has further evolved and modified the sediments, and has also been an important factor in the development and distribution of the pore-laminar fracture system. In the process of diagenesis, the organic-rich laminated limestone was mainly affected by calcite recrystallization and dissolution. The organic-rich laminated mudstone was dominated by clay mineral transformation and thermal evolution of organic matter. Clarification of the distribution pattern and development control factors of the pore-laminar fracture systems is of great significance for guiding the exploration and development of shale oil in the Jiyang Depression.

Key words: pore-laminar fractures systems; lithofacies; continental shale; formation mechanism; shale oil