

陆相和海相页岩储层孔隙结构差异性分析

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摘要:页岩储层以微-纳米孔隙和裂缝作为页岩油气的赋存空间,对其孔隙结构特征的研究是明确页岩油气富集机理的关键,而陆相和海相页岩储层的孔隙结构特征存在巨大的差异。为此,运用场发射扫描电镜、CO₂吸附、N₂吸附、高压压汞分析和索氏抽提等方法,以沾化凹陷沙三段下亚段陆相页岩储层和川东南龙马溪组海相页岩储层为典型实例,深入分析陆相和海相页岩储层的孔隙结构差异。结果表明,沾化凹陷沙三段下亚段陆相页岩储层中有机质单体内部并未发育密集分布且相互连通的蜂窝状孔隙,具有极大孔体积的宏孔更为发育,能够为游离烃赋存提供良好的储集空间,控制着页岩油的富集。而川东南龙马溪组海相页岩储层中有机质单体内部密集发育相互连通的蜂窝状孔隙,具有极大比表面积的微孔最为发育,能够为吸附烃赋存提供足够的比表面,控制着页岩气的富集。

关键词:陆相;海相;页岩储层;孔隙结构;差异性

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Analysis of differences in pore structure between continental and marine shale reservoirs

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Abstract: Since shale oil and gas occur in micro-to nano-pores and fractures, researches on pore structure characteristics of shale reservoirs are important to understand the accumulation mechanism of shale oil and gas. There are great differences in pore structure between continental and marine shale reservoirs. In order to analyze their differences in pore structure, several methods including field emission-scanning electron microscopy, CO₂ adsorption, N₂ adsorption, high-pressure mercury injection, and Soxhlet Extraction, etc. were applied to analyze samples from the lower submember of 3rd member of Eocene Shahejie Formation (Es₃¹) continental shale in Zhanhua Sag and Longmaxi Formation marine shale in Sichuan Basin. The results show that interconnected honeycomb-shape pores are not developed within organic matter for Es₃¹ shale in Zhanhua Sag. In addition, macro-pores with great pore volume are well-developed, providing good spaces for free hydrocarbon storage and controlling shale oil accumulation. In contrast, interconnected honeycomb-shape pores are well-developed

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within organic matter for Longmaxi Formation marine shale in Sichuan Basin. Micropores with great specific surface area provide sufficient spaces for absorbed hydrocarbon and control shale gas accumulation.

Key words: lacustrine facies; marine facies; shale reservoirs; pore structure; difference

页岩油气已经成为北美油气工业的重要能源之一,北美页岩油气勘探开发所取得的巨大成功引起了世界各国对于页岩油气的广泛关注^[1-4]。近年来,中国的地质工作者也开始了针对页岩油气的研究,页岩油气资源逐渐成为中国油气勘探的重要对象^[5-7]。

页岩油气主要以吸附态、游离态和溶解态赋存于富有机质页岩的微-纳米孔隙及裂隙中^[8]。页岩微-纳米孔隙结构对于页岩油气的储集和运移具有重要的控制作用,其主要通过孔隙的类型、大小、形状、体积、比表面积和连通性等特征来体现^[9-11]。不同沉积环境下形成的页岩储层微-纳米孔隙结构特征截然不同。相比于海相页岩储层,陆相页岩储层具有沉积环境相变快以及沉积地层新的特点,因此两者的孔隙结构特征具有明显的差异性。为此,笔者以沾化凹陷沙三段下亚段陆相页岩和川东南龙马溪组海相页岩为典型实例,对比陆相和海相页岩储层之间孔隙结构特征的差异,以期为后续的陆相和海相页岩油气勘探开发提供依据。

1 区域地质概况

沾化凹陷位于渤海湾盆地济阳拗陷的东北部,南邻陈家庄凸起,东邻垦东凸起,西侧和北侧分别以义东断层和埕东断层为界,面积为2 800 km²,发育孤北洼陷、渤南洼陷、孤南洼陷、富林洼陷、四扣洼陷、垦西洼陷和孤岛凸起等多个次级构造单元^[12-16](图1)。沾化凹陷内部发育大套的泥页岩层系,其中沙三段下亚段是泥页岩的主要发育层位,也是页岩油勘探的重要层位^[17-20]。目前已有多口井在沙三段下亚段钻遇页岩油藏,并且获得高产的工业性油流^[17-18]。样品取自沾化凹陷罗家鼻状构造的罗69井,自上而下依次钻遇新生界第四系平原组、新近系明化镇组及馆陶组、古近系东营组及沙河街组,其中沙三段下亚段为本次研究的目的层段,埋深为2 910~3 130 m,地层厚度达220 m,该井为沾化凹陷唯一的系统取心井,于埋深2 911.00~3 140.75 m连续钻井取心29次,累积取心长度达221.36 m。岩性以泥页岩为主,整体较为致密,颜色为灰色和深灰色,微裂缝普遍发育,有明显的油迹和油斑分布。

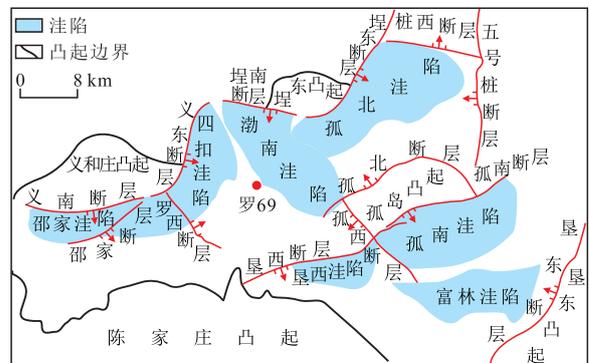


图1 沾化凹陷区域构造位置

Fig.1 Location of the study area in Zhanhua Sag

川东南属于上扬子台内拗陷构造单元^[21-24](图2),早期为深水陆棚沉积,后期逐渐向浅水陆棚和潮坪沉积演化^[25]。其构造复杂,褶皱与断层相间分布,且断层的延伸方向和褶皱的走向基本一致,均为NNE向或NE向,其中以NNE向为主。川东南龙马溪组发育一套稳定的海相富有机质页岩,具有页岩气形成的良好地质条件,黔页1井的试气点火成功显示了川东南龙马溪组页岩具有极大的开发潜力^[26]。

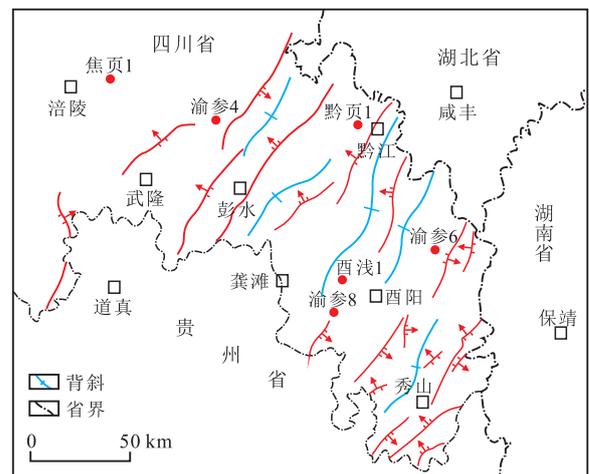


图2 川东南区域构造位置

Fig.2 Location of the study area in southeastern Sichuan Basin

2 孔隙类型的差异

由于沾化凹陷沙三段下亚段陆相页岩的热演化程度相对较低,镜质组反射率为0.70%~0.93%(图3a),处于成熟阶段,以生油为主,有机质单体常呈相对致密的条带状或块状(图4a,4b),尽管也会

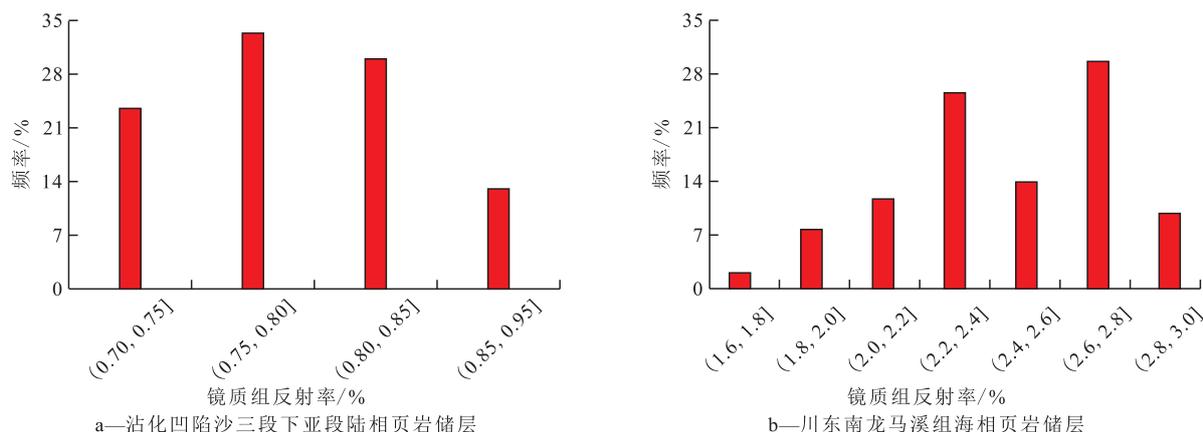


图3 镜质组反射率频率分布
Fig.3 R_0 frequency distribution histograms

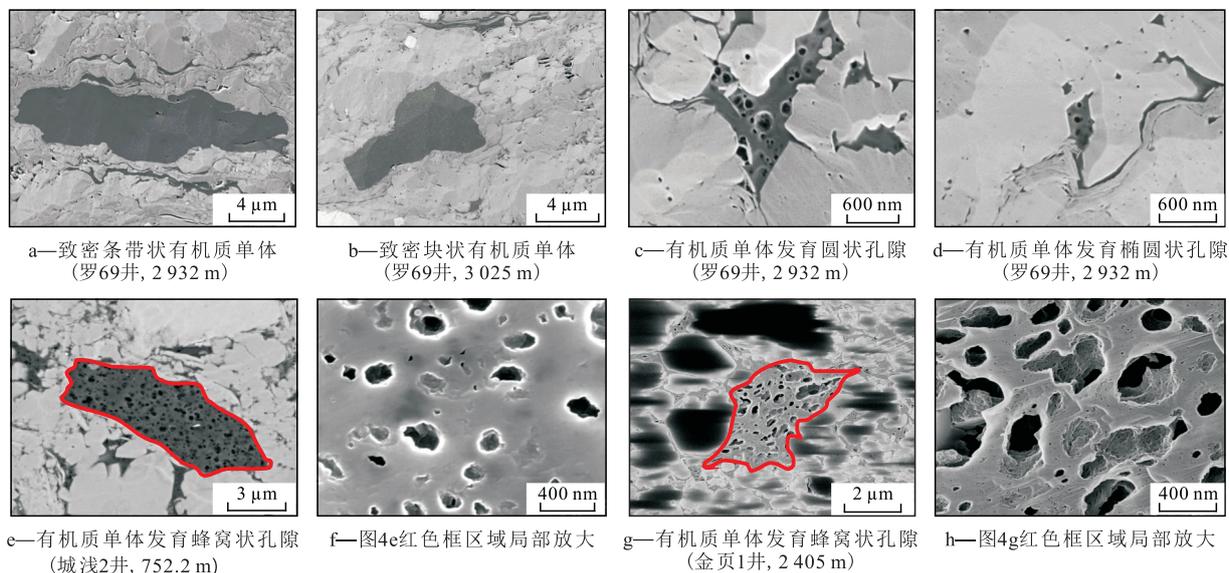


图4 有机质孔隙扫描电镜图像
Fig.4 SEM images of organic pores

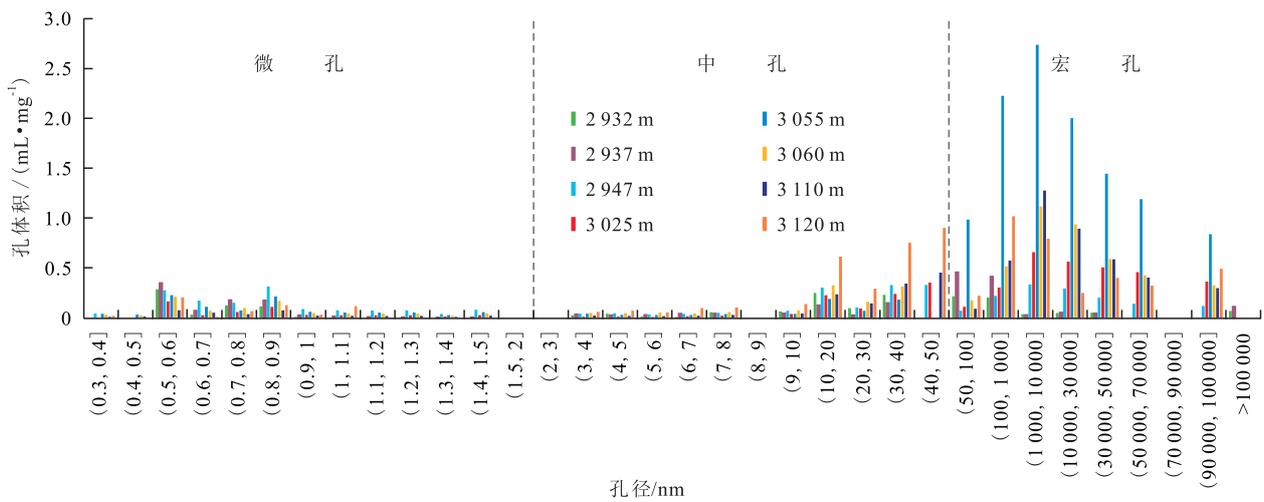
发育一些圆状、椭圆状的孔隙(图4c, 4d),但并不发育密集分布且相互连通的蜂窝状孔隙。与之相反的是,川东南龙马溪组海相页岩储层有机质热演化程度已处于过成熟阶段,镜质组反射率为1.73%~2.99%(图3b),以生气为主,有机质单体内部密集发育蜂窝状孔隙(图4e—4h),这些有机质孔隙连通性好,能够为页岩气吸附提供足够的比表面积,同时也是页岩气运移的主要渗流通道^[27]。

3 孔径分布的差异

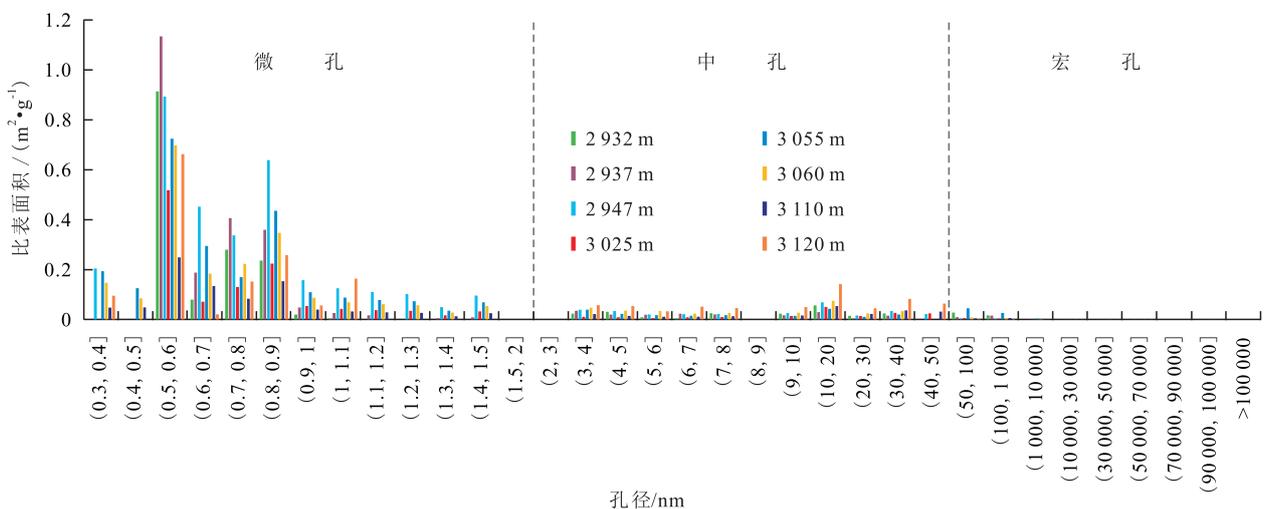
沾化凹陷沙三段下亚段陆相页岩储层的孔体积分布在10~100 000 nm的孔径范围内呈现一定的峰值特征,但不同样品之间的非均质性较大(图5a),而比表面积分布在0.5~0.9 nm的孔径范围内呈明显的峰值特征(图5b)。孔体积主要由中孔和宏

孔提供,以宏孔为主,宏孔占总孔体积的56.28%,中孔占总孔体积的25.77%,而微孔贡献率最低,仅占总孔体积的17.95%;比表面积则主要由微孔和中孔提供,以微孔为主,微孔占总比表面积的84.80%,中孔占总比表面积的14.08%,而宏孔仅贡献了总比表面积的1.12%(图6)。因此,沾化凹陷沙三段下亚段陆相页岩储层中宏孔最为发育,其次是中孔,微孔发育最差。

与之相反的是,川东南龙马溪组海相页岩储层的孔体积分布呈多峰特征^[22],峰值集中分布在0.3~0.6, 1.5~4和10 000~70 000 nm的孔径范围内,并且不同样品的孔体积分布特征较为相似(图7),而比表面积分布则在0.3~0.6和1.5~4 nm的孔径范围内呈现峰值特征,且在0.3~0.6 nm孔径范围内的峰值较大。孔体积主要由微孔和中孔提供,其中微孔占总孔体积的35%,中孔占41%,而宏孔的贡献率最



a—孔体积随孔径分布



b—比表面积随孔径分布

图5 沾化凹陷罗69井沙三段下亚段陆相页岩储层不同孔径下的孔体积和比表面积分布

Fig.5 Pore volume and specific surface area distribution of different pores in Lower Es₃ Member continental shale in Well Luo69, Zhanhua Sag

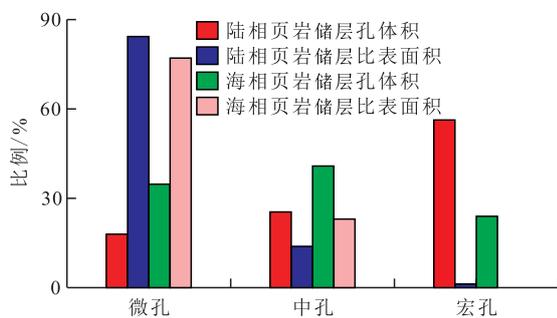


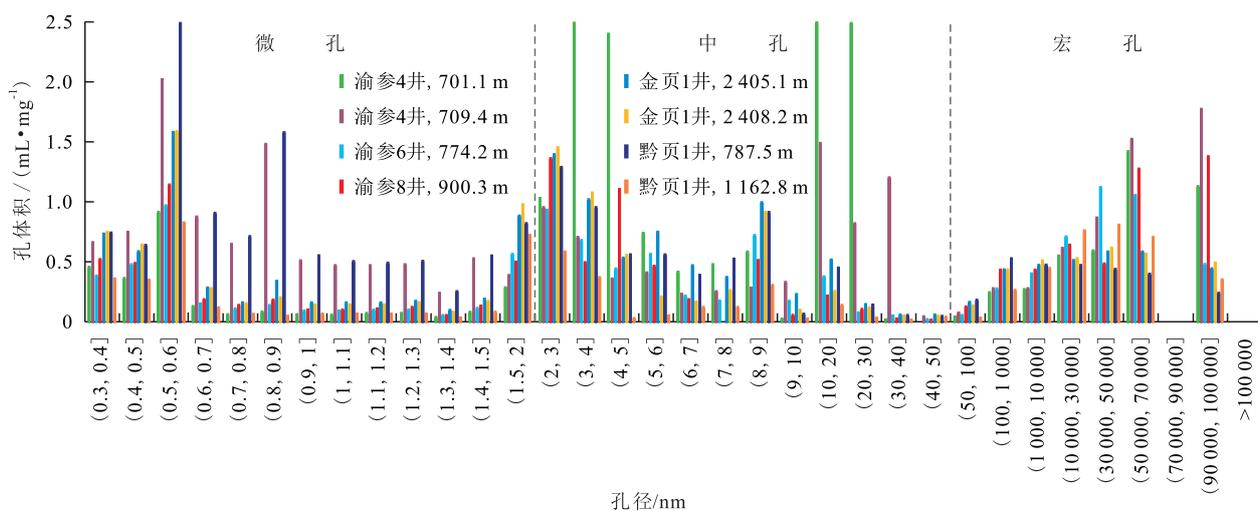
图6 不同尺度孔隙对页岩储层孔体积和比表面积的贡献率

Fig.6 Bar graphs showing the contributions of shale reservoir pores at different scales to pore volume and surface area

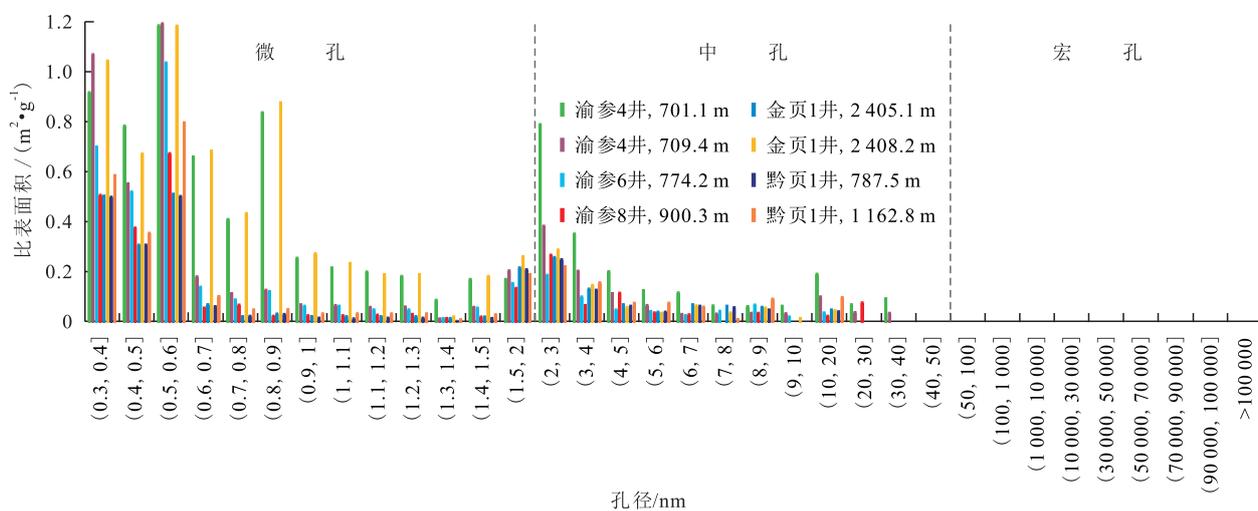
低, 占总孔体积的24%; 比表面积同样也由微孔和中孔提供, 以微孔为主, 微孔占总比表面积的76.87%, 中孔占23.05%, 而宏孔仅贡献了0.08%的

比表面积(图7)。因此, 川东南龙马溪组海相页岩储层中微孔最发育, 其次是中孔, 而宏孔发育最差。

造成陆相和海相页岩储层孔隙结构差异的原因在于, 沾化凹陷沙三段下亚段陆相页岩储层的主要矿物为方解石、黏土矿物和石英, 其中方解石含量最高, 平均高达51.88%, 而黏土矿物和石英含量均相对较低, 平均分别为18.97%和18.11%(图8); 而川东南龙马溪组海相页岩储层则以石英和黏土矿物为主, 石英含量为28.3%~69.5%, 黏土矿物含量为20.4%~57.6%, 平均含量均高达41.8%, 方解石含量为4.0%~32.4%, 平均仅为11.9%(图8)。高的黏土矿物和硅酸盐矿物含量有利于微孔发育, 而高的碳酸盐矿物含量则有利于中孔和宏孔发育。因此, 沾化凹陷沙三段下亚段陆相页岩储层的孔隙发育程度由大到小依次为宏孔、中孔、微孔, 而川东南



a—孔体积随孔径分布



b—比表面积随孔径分布

图7 川东南龙马溪组海相页岩储层不同孔径下孔体积和比表面积分布(据姜振学等^[22]修改)

Fig.7 Pore volume and specific surface area distribution of different pores in Longmaxi marine shale in southeastern Sichuan Basin(modified according to JIANG Zhenxue et al^[22])

龙马溪组海相页岩储层的孔隙发育程度由大到小依次为微孔、中孔、宏孔。此外,纹层的广泛发育也是沾化凹陷沙三段下亚段陆相页岩储层中宏孔发育的重要原因,而高的有机质热演化程度促使川东南龙马溪组海相页岩储层发育大量有机质微孔^[27]。

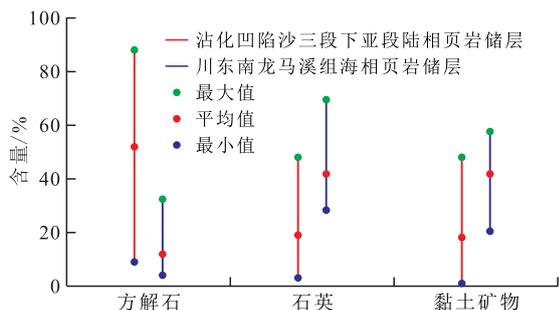


图8 页岩储层全岩矿物组成

Fig.8 Triangular charts of the rock mineral composition in shale reservoirs

4 孔隙结构对含油气性控制作用的差异

众所周知,吸附烃主要附着于有机质和无机矿物颗粒的表面,而游离烃则主要储存于页岩储层的孔隙和微裂缝中。因此,吸附烃含量与比表面积密切相关,而游离烃含量则主要受孔体积控制^[22]。

对于沾化凹陷沙三段下亚段陆相页岩储层而言,残留烃含量与宏孔的孔体积呈明显的正相关关系,而与微孔和中孔的孔体积无明显相关关系(图9a)。这是由于微孔和中孔对孔体积的贡献有限,进而对于游离烃的富集作用较弱。因此,具有极大孔体积的宏孔决定着游离烃的富集,能够为页岩提

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