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鄂尔多斯盆地合水地区长7致密油岩性岩相类型识别及其应用

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提要:利用岩心、薄片、常规测井、成像测井等资料结合物性分析等,对鄂尔多斯盆地合水地区长7致密油岩性岩相等特征进行了研究。长7致密油储层以砂质碎屑流、浊流和滑塌成因的砂岩为主,烃源岩以泥岩、油页岩为主,根据粒度参数进一步将长7致密油岩性岩相划分为砂质碎屑流细砂岩相、浊流细砂岩相、浊流粉砂岩相、滑塌岩相、半深湖—深湖泥岩相以及油页岩相6类。通过岩心刻度常规和成像测井,建立了不同岩性岩相的测井识别评价标准,并实现了各单井纵向上的岩性岩相的识别和划分。在此基础上,进一步探讨了不同岩性岩相与TOC含量和脆性指数的关系。最后结合试油气资料和油气解释结论,阐明岩性岩相对致密油储层物性和含油气性的定量控制。致密油岩性岩相的研究可为后期成岩相、孔隙结构以及优质储集体预测等奠定基础,为研究区长7致密油的综合评价和有利发育区带预测提供理论指导和技术支持。

关 键 词:岩性岩相;致密油;TOC;脆性指数;长7段;合水地区;鄂尔多斯盆地

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Identification of lithology and lithofacies type and its application to Chang 7 tight oil in Heshui area, Ordos Basin

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Abstract: The characteristics of lithology and lithofacies in Chang 7 tight oil in Heshui area, Ordos Basin, were studied by such means as core observation, traditional thin section analysis, conventional logging and imaging logging processing, combined with

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general physical analysis. Chang 7 tight oil reservoir is mainly sandstone caused jointly by sandy debris flow, turbidity current and slump, and source rocks are mainly mudstone and oil shale. According to grain size parameters, Chang 7 tight oil is further divided into six kinds of lithology and lithofacies, i.e., fine sandstone of sandy debris flow, fine sandstone of turbidity current, siltstone of turbidity current, fluxoturbidite, mudstone of semi−deep water or deep water and oil shale. According to conventional logging and imaging logging scaled by core data, the authors established the evaluation criteria of well logging identification in different kinds of lithology and lithofacies, realized the identification and classification of lithology and lithofacies in a single well on the longitude, and further explored the relationship between different kinds of lithology and lithofacies and TOC content as well as brittleness index. Finally oil− gas testing data and oil− gas interpretation results were combined to illuminate the quantitative control of lithology and lithofacies on physical property and oil−gas possibility of tight oil reservoir. The study of lithology and lithofacies of tight oil can lay the foundation for the further analysis of lithogenous phase and pore structure as well as the prediction of high quality reservoir. It can also provide theoretical guidance and technical support for the comprehensive assessment of Chang 7 tight oil and the prediction of favorable zones for oil−gas reservoir development.

Key words: lithology and lithofacies；tight oil；TOC；brittleness index；Chang 7；Heshui area；Ordos Basin

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随着常规油气勘探难度的增加，非常规油气资源在现今油气勘探领域中得到越来越多的关注[1−2]。致密油藏属于非常规油气资源，一般构造简单，储量巨大，孔渗性差，其物性和含油气性主要受岩性岩相控制[3]。一定的岩性岩相带是储集体发育的必要条件，致密油气往往富集于岩性较纯、岩相较优的有利岩性岩相带。本文在综合利用岩心、测井资料的基础上，对由重力流沉积形成的致密油层段的岩性岩相进行单井纵向上的划分与特征研究，不同岩性岩相垂向上的叠置序列可为砂体结构分析提供借鉴；同时对致密油不同岩性岩相的烃源岩品质（TOC）、脆性矿物组分含量的对应关系进行分析；最后结合试油气资料和油气解释结论，阐明了不同岩性岩相对致密油储层物性和含油气性的定量控制。

鄂尔多斯盆地合水地区位于甘肃省庆阳市合水县境内，构造位置位于鄂尔多斯盆地陕北斜坡西南缘（图1），该区构造平缓，在西倾单斜背景上局部发育小型鼻状隆起[4−6]。延长组是在鄂尔多斯盆地持续坳陷和稳定沉降过程中堆积的河流−湖泊相陆源碎屑岩系，纵向上分为10个油层组[7]。长7段沉积时，盆地处于最大湖泛期，湖盆中心与斜坡发育大面积的砂质碎屑流和浊积扇砂体，导致长7段岩性致

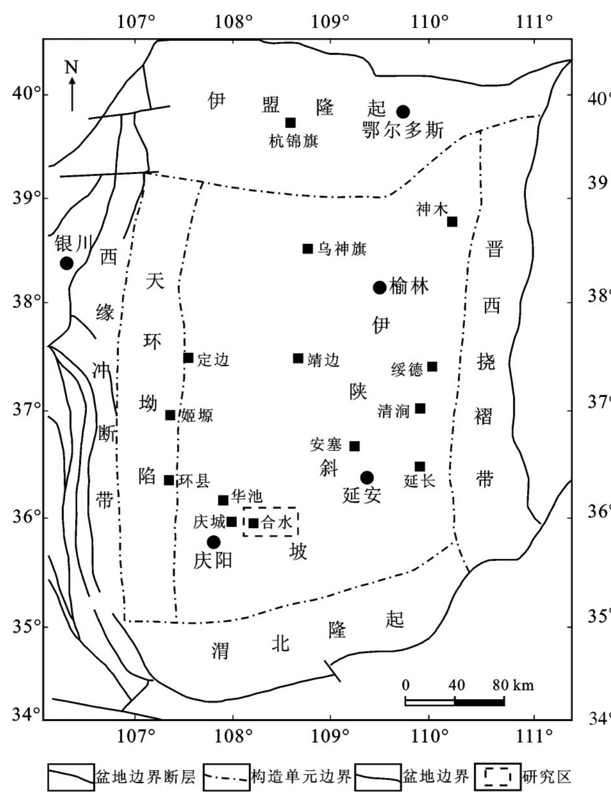

图1 工区构造图（据文献[6]修改）
Fig.1 Structural map of the work area (after reference [6])

密复杂[8-13]。合水地区在长7_3沉积了厚层优质烃源岩,长7_1、长7_2则发育多期三角洲以及重力流成因砂体,该区发育的砂质碎屑流、浊流和滑塌成因的砂岩与长7_3发育的烃源岩源储一体或紧邻,为致密油的形成提供了良好的条件[14-18]。

1　烃源岩及储层基本特征

鄂尔多斯盆地合水地区长7致密油烃源岩分布较广,主要发育在长7段底部。岩性主要以页岩、油页岩以及黑色泥岩为主,厚度一般30~50 m。其母质类型以腐泥—混合型为主,有机质丰度高,类型好,是优质的烃源岩[18-19]。

长7致密油储层岩性主要为砂岩、泥岩以及油页岩。其中砂岩主要为岩屑砂岩、岩屑长石砂岩和长石岩屑砂岩(图2)。石英含量主要分布在12%~63.5%,平均39%;长石含量8.5%~46%,平均21%,以钾长石和钠长石为主;岩屑20%~61%,平均38%,以变质岩岩屑和岩浆岩岩屑为主,沉积岩岩屑较少。储层粒度主要为细砂、粉砂级别,磨圆为次棱角状,分选中等—差等。储层填隙物含量较高,黏土杂基为主,还包括自生石英,碳酸盐岩以及伊利石、伊蒙混层和绿泥石等黏土矿物胶结物。

鄂尔多斯盆地合水地区长7致密油储层物性较差,孔隙度分布在0.37%~17.74%,平均9.17%,地面空气渗透率分布在0.001×10^{-3}~2.56×10^{-3} μm²,平均

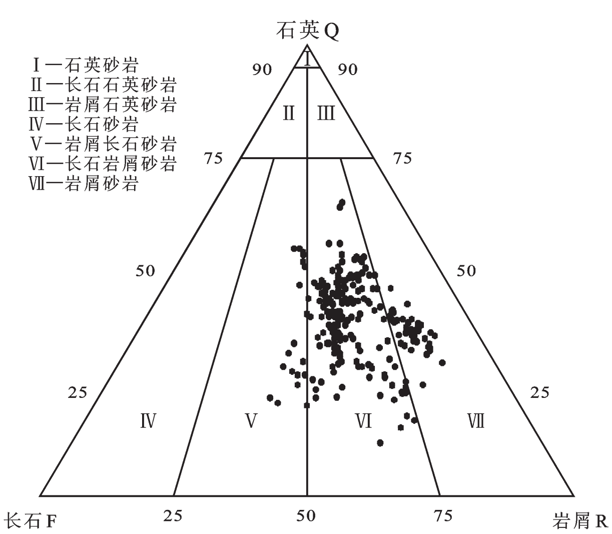

图2 合水地区长7油层组致密油储层成分三角图
Fig.2 Triangular diagram of the composition of Chang 7 tight oil reservoir in Heshui area

0.11×10^{-3} μm²。大部分样品渗透率均小于1.0×10^{-3} μm²,具有典型的致密油储层特征。

2　致密油岩性岩相特征

在鄂尔多斯合水地区不同位置和层段,岩性及其组合特征存在较大差异。单井纵向上岩性岩相的叠置关系的精细描述与岩心的观察描述,可为砂体结构分析提供借鉴。结合岩心、测井资料,将研究区划分为砂质碎屑流细砂岩相、浊流细砂岩相、浊流粉砂岩相、滑塌岩相、半深湖—深湖泥岩相和油页岩相共6个岩性岩相,其中砂质碎屑流细砂岩相、浊流细砂岩相、浊流粉砂岩相和滑塌岩相为储集相,泥岩相和油页岩相为烃源岩相。

2.1　砂质碎屑流细砂岩相

砂质碎屑流是三角洲前缘砂体在外界触发力作用下滑动崩塌而形成,多发育于湖盆中部[20-21]。岩心观察可得到砂质碎屑流主要特征以细砂岩为主,具有块状构造,分选较好,部分块状砂岩顶部发育薄层的平行层理,具有滑水面,可能是由于砂质碎屑流向牵引流转化而形成(图3-a);砂岩底部含大量植物碎屑,无定向分布(图3-b);多富含黑色角砾状泥岩撕裂屑且部分被剥蚀,黑色泥砾是内源型泥岩碎屑,毛刺发育,具有定向性或成层性,反映沉积体呈层状运动且经过短距离搬运快速沉积(图3-c);泥砾较大,磨圆好,颜色氧化成浅黄色,此类泥砾形成于三角洲平原(图3-d);砂质碎屑流底部发育负载构造(图3-e)[22]。

砂质碎屑流相在常规测井曲线上表现为中低电阻(50~100 Ω·m)、低伽马(80~130 API)、低声波时差(60~90 μs/ft)、泥质含量小于20%,均质厚层砂体的伽马曲线常呈箱形,多个砂体叠加时伽马曲线常呈齿状箱形或钟形[23];在成像测井上表现为均质亮色块状厚层偶含暗色极薄层的泥岩撕裂屑(图4)。

2.2　浊流细砂岩相和浊流粉砂岩相

湖相浊流沉积是指沉积物重力流在深湖、较深湖区环境中形成的重力流沉积,是密度流的一种特殊形式,其内部最突出的特征就是粒级递变构造,即鲍马序列[24-25]。浊流细砂岩主要分布在浊流相的下部,发育正粒序和平行层理(图3-f),为鲍马序列的A、B段;浊流粉砂岩相主要分布在浊流相的上部,发育砂纹层理(图3-g),相当于鲍马序列的D、

图3 各岩性岩相的岩心特征

a—块状细砂岩和粉砂岩，整体呈均质块状，原始物质分选较好，部分块状砂岩顶部发育薄层的平行层理；b—砂岩底部含大量植物碎屑，无定向分布；c—富含黑色角砾状泥岩撕裂屑且部分被剥蚀，黑色泥砾是内源型泥岩碎屑，毛刺发育，具有定向性或成层性；d—泥砾较大，磨圆好，颜色氧化成浅黄色；e—底部发育负载构造；f—浊流底部正粒序层理和平行层理；g—浊流上部砂纹层理；h—浊积岩底部形成槽模等底层面构造；i—发育火焰构造等同生变形构造；j—滑塌岩多为粉砂质泥岩或粉砂岩，发育包卷层理和小型褶皱构造，底部发育滑动面，界面上下岩性差异显著，砂泥高度混杂，整体呈块状；k—泥岩含黑色炭化的植物碎屑；l—油页岩发育页理，可见暗色斑点状的黄铁矿

Fig.3 Core facies characteristics of each lithology and lithofacies

a−The massive fine sandstone and siltstone are in homogeneity with good sorting of prime matter, and part of the massive sandstone develops thin layer of parallel bedding on the top; b−Plant debris is developed at the bottom of sandstone without orientation; c−Sandstone is rich in black brecciform mudstone debris with partial denudation, and the black boulder clay is endogenous mudstone debris with burr shape, directionality or stratification; d− The large boulder clay is in good rounding and presents light yellow due to oxidation; e −Load structure is developed at the bottom; f− Normal graded bed sequence and parallel bedding are developed at the bottom of turbidity current; g− Lamina is developed on the top of turbidity current; h−Bottom bedding plane structures such as flute cast are developed at the bottom of turbidite; i− Flamy structure and other contemporaneous deformed structures are developed; j− Lithology of fluxoturbidite is mainly silty mudstone and siltstone, developing convolute bedding and small fold structure, and exhibiting massive shape, with sliding surface at the bottom, significant difference of lithology and mixture of sandstone and mudstone; Fig. K−Mudstone develops black charry plant debris; l− Oil shale develops lamella with dark color of pyrite in mottled distribution

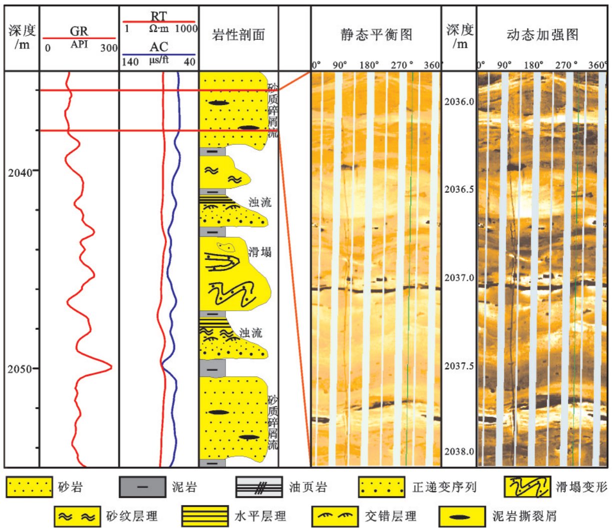

图4 砂质碎屑流细砂岩相常规及成像测井特征
Fig.4 Conventional logging and imaging logging characteristics of fine sandstone of sandy debris flow

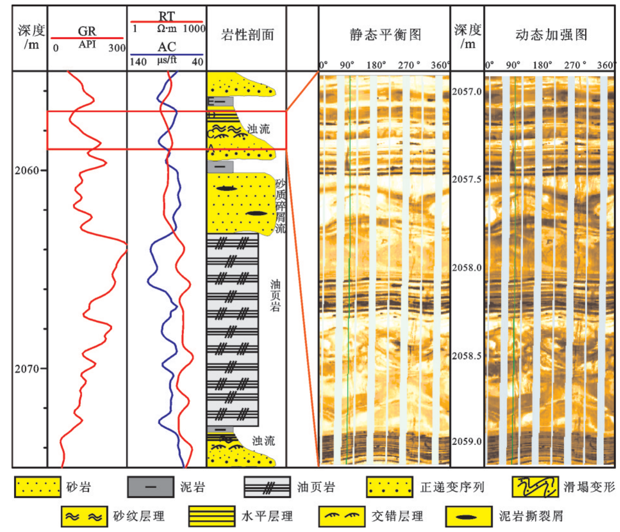

图5 浊流相的互层特征
Fig.5 Interbed characteristics of turbidity sandstone

C、E段。浊积岩底部形成槽模等底层面构造（图3–h）；发育火焰构造等同生变形构造（图3–i）；底部为与下伏突变、顶部渐变的岩性接触关系。

浊流相在常规测井曲线上表现为低电阻（40~80 Ω·m）、中高伽马（150~200 API）、中声波时差（80~100 μs/ft）、泥质含量20%~70%，伽马曲线多为齿状近箱形或钟形曲线频繁叠加[24]；在成像测井上表现为暗色相对低阻的粉砂岩与亮色相对高阻的细砂岩互层，单段互层厚度不大，为1 m左右（图5）。

2.3 滑塌岩相

滑塌岩是滑塌作用较强烈阶段的产物，与碎屑流沉积的主要区别之一是与下伏层不一定有突变界面，向下和向上与正常层之间均可呈渐变接触[22]。由岩心观察可看出滑塌岩多为粉砂质泥岩或粉砂岩，发育包卷层理和小型褶皱构造，底部发育滑动面，界面上下岩性差异显著；砂泥高度混杂，整体呈块状（图3–j）。

滑塌岩在常规测井曲线上主要表现为中低电阻（50~100 Ω·m）、中低伽马（100~150 API）、中声波时差（80~100 μs/ft）、泥质含量20%~70%，伽马曲线多为齿状；在成像测井上较易识别，常呈亮暗混杂的块状形态，可见滑塌变形构造（图6）。由于滑塌岩在测井曲线上较难识别，因此滑塌岩相在本次的岩性岩相测井评价分析中不做重点介绍。

2.4 半深湖—深湖泥岩相

研究区泥岩主要为灰黑色、黑色，均质块状，发育广泛且连续厚度较大，多含黑色炭化的植物碎屑，局部层段发育水平层理（图3–k）。

常规测井曲线上表现为中低电阻（50~100 Ω·m）、中高伽马（150~200 API）、中高声波时差（90~110 μs/ft）、泥质含量大于70%；成像测井上呈暗色块状，水平层理发育（图7）。

2.5 油页岩相

合水地区长7段油页岩多见于底部，属于大型内陆湖盆的湖相油页岩[7,26]，厚度8~15 m，品质好、成熟度是适中，内部发育页理，见暗色斑点状的黄铁矿（图3–l）。

测井曲线上具有高电阻（100~200 Ω·m）、高伽马（>250 API）、高声波时差（100~130 μs/ft）、泥质含量大于70%等特征；成像测井上呈现高亮的厚层，斑点状黄铁矿沿页理发育（图8）。

3 岩性岩相对TOC和脆性指数的定量控制

总有机碳含量（TOC）是评价致密油的一个重要参数，它反映了有机质含量多少及烃源岩生烃潜力的大小，对于致密油烃源岩特性评价有重要意义[27]。测井资料具有纵向连续性好、分辨率高的特

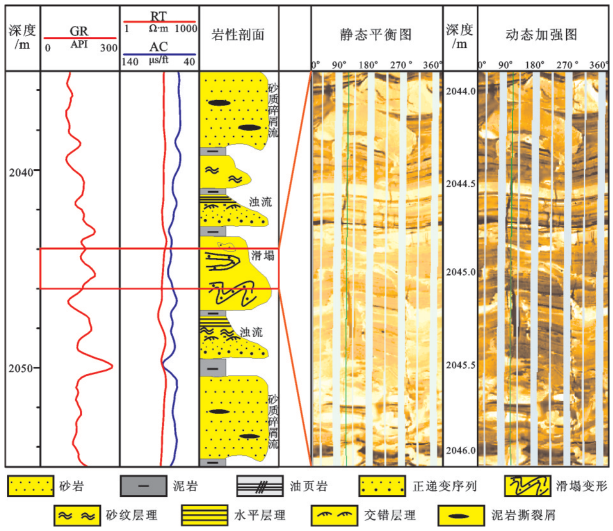

图6 滑塌变形形成的砂岩岩脉

Fig.6 Sandstone dykes caused by slump and deformation

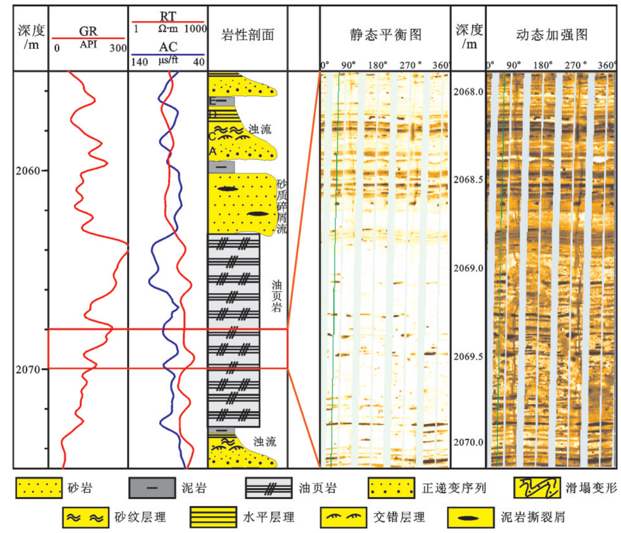

图8 油页岩常规测井及成像测井特征

Fig.8 Conventional logging and imaging logging characteristics of oil shale

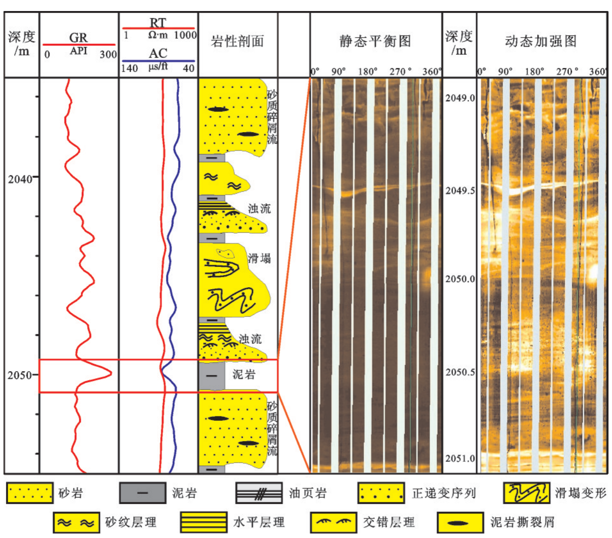

图7 泥岩常规测井及成像测井特征

Fig.7 Conventional logging and imaging logging characteristics of mudstone

征，故可以利用测井资料评价致密油层的总有机碳含量。

致密油砂岩储层的渗透率一般比较低，使得自然产能同样很低，因此通常需要进行压裂改造。岩石的脆性不仅决定了天然裂缝的发育程度还决定了压裂改造的难易，因此对于致密油而言，岩石的脆性评价尤为重要[28]。对岩石的脆性评价可用矿物组分法[29−30]计算岩石的脆性指数。由砂泥岩矿物组分定量评价结果可以得到石英、方解石、白云石和黏土的体积分数，则计算脆性指数的计算公式为：

$$BI=K\times\frac{V_{qa}+V_{ca}+V_{do}}{V_{qa}+V_{ca}+V_{do}+V_{cl}}\times 100\%$$

式中，V_{qa}、V_{ca}、V_{do}、V_{cl}为石英、方解石、白云石和黏土的体积分数，K为地区修正系数。

鄂尔多斯盆地合水地区长7致密油层组的TOC值是地球化学分析实测得到，脆性指数由矿物组分法计算得出。TOC反映了有机质的含量和生烃潜力，脆性指数反映了压裂难易，因此不同岩性岩相与两个参数指标具有一定对应关系。由图9看出，砂质碎屑流细砂岩有机质含量很低，TOC值接近于0；石英、方解石等含量高，黏土含量低，脆性指数最大可达70%。浊流细砂岩相所含总有机碳含量较低，TOC值均小于10%；脆性指数主要分布在30%~60%。浊流粉砂岩相与细砂岩相类似，但比前者TOC值略高、脆性指数略低。泥岩相所含有机质含量较高，TOC值小于15%，主要集中在3%~10%；脆性指数一般小于40%。油页岩相TOC含量最高，TOC值一般大于15%；脆性指数小于20%（图9）。总体来说，TOC值和脆性指数与不同岩性岩相成较好的对应关系：从砂质碎屑流细砂岩相到深湖油页岩相，有机质含量增加，储集相逐渐过渡到烃源岩相，TOC值增大；同时，砂质含量降低，石英、方解石

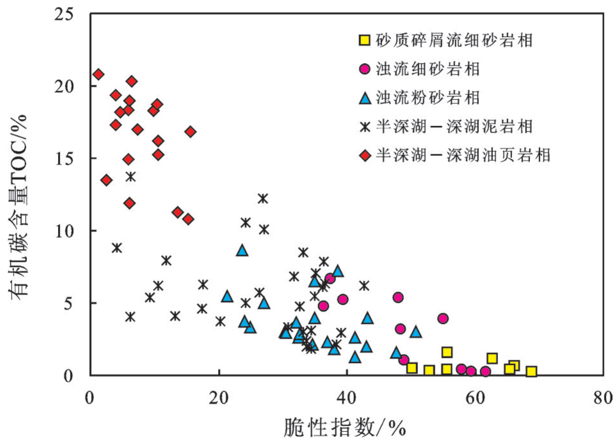

图9 岩性岩相与TOC和脆性指数的关系
Fig.9 Relationship of the lithology and lithofacies with the TOC and brittleness index

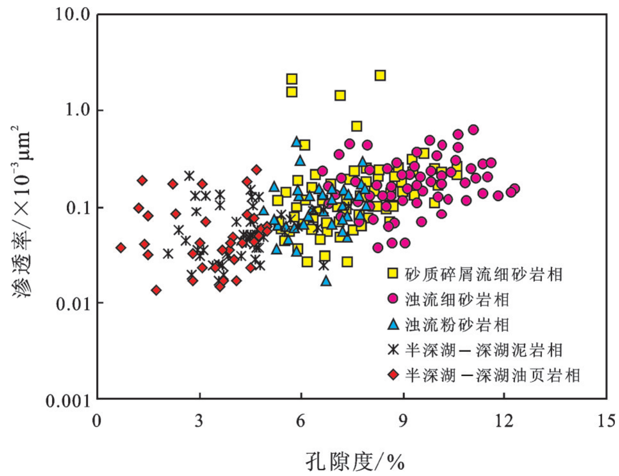

图10 不同岩性岩相的物性参数图
Fig.10 Physical property parameters of different kinds of lithology and lithofacies

等脆性矿物含量减少，黏土等塑性矿物含量增加，使得脆性指数降低。

4　岩性岩相对致密油储层物性和含油气性的定量控制

岩性岩相反映了岩石的沉积环境、沉积水动力的变化、岩石结构构造特征以及影响岩石储集物性的成分成熟度和结构成熟度，因此可在一定程度上指示储层物性的变化[31]。如不考虑成岩及其后生作用的影响，在大的构造、沉积背景下，岩性岩相对储层物性的控制作用明显，优质储集体一般形成于具有较高孔渗的岩性岩相带[31]。事实上，岩性岩相类型宏观上控制着在纵向与平面上砂体及优质储层的分布，其研究可以分析有利的油气储集空间及油气聚集区带，对于新的勘探区域具有良好的预测作用。

致密油的孔隙度和渗透率数据一般由氦气法测试得到。不同岩性岩相与储层物性有较好的对应关系：半深湖–深湖泥岩相和油页岩相的孔隙度和渗透率均较低（孔隙度一般小于6%，渗透率一般小于$0.1\times10^{-3}\mu m^2$）；浊流相孔渗较泥岩相和油页岩相好，其中浊流粉砂岩相孔隙度主要在6%左右，浊流细砂岩相孔隙度相对较高，主要分布在7%~12%范围内，渗透率均在$0.1\times10^{-3}\mu m^2$左右；砂质碎屑流细砂岩相孔隙度分布在6%~11%，渗透率分布范围不等，渗透率总体大于其他类岩相其原因是砂质碎屑流含较多石英、长石等脆性矿物，易产生微裂缝使得砂体渗流能力相对较大。总体来看，浊流细砂岩岩相综合物性最好，其次是砂质碎屑流细砂岩相（图10）。

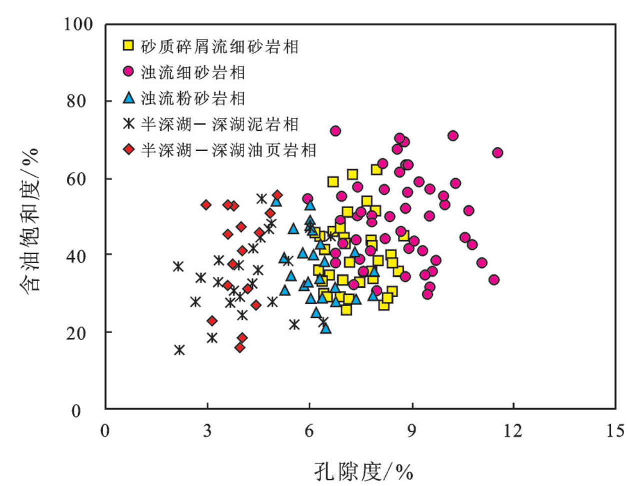

图11 不同岩性岩相对含油气性的控制
Fig.11 The control of oil-gas possibility by different kinds of lithology and lithofacies

不同岩性岩相也控制着致密油含油气性。总体来看，如不考虑成岩及其后生作用的影响，浊流细砂岩相含油气性最好，含油饱和度和孔隙度范围均最大；砂质碎屑流细砂岩相的含油气性次之；半深湖–深湖泥岩相和油页岩相的综合含油气性均较差（图11）。

5 结 论

（1）鄂尔多斯合水地区共划分6个岩性岩相，分别为砂质碎屑流细砂岩相、浊流细砂岩相、浊流粉砂岩相、滑塌岩相、半深湖—深湖泥岩相和油页岩相，每个岩性岩相都具有典型的岩心、常规测井、成像测井特征。

（2）TOC反映了有机质的含量和生烃潜力，脆性指数反映压裂难易。由测井资料实测和计算分别得到的TOC值和脆性指数与不同岩性岩相有较好的对应关系，其中砂质碎屑流细砂岩相TOC值最低，脆性指数最大；其次分别为浊流细砂岩相、浊流粉砂岩相、泥岩相；油页岩相的TOC值最高，脆性指数最低。

（3）岩性岩相类型控制着砂体及优质储层在横纵向上的分布，其研究可以分析有利的油气储集空间及油气聚集区带。其中鄂尔多斯致密油储层浊流细砂岩相的物性、含油性最好，其次是砂质碎屑流细砂岩相。

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