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中国陆相页岩油分类及其意义

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摘要:中国陆相页岩油资源潜力巨大,是中国常规油气的重要战略接替资源。然而,陆相页岩油研究基础薄弱、成因和富集机理不清、“甜点”评价难度较大且标准不一,严重制约着这些资源的开发利用。基于前人研究成果,立足于勘探开发实际,建立了一套简化的陆相页岩油分类评价标准。依据页岩油储集岩石类型和赋存空间,将其分为夹层型、裂缝型和纯页岩型,重点讨论了纯页岩型页岩油。依据纯页岩型页岩油的沉积构造,将其划分为纹层状、层状和块状页岩油。划分方案中未将岩石颗粒粒径作为划分页岩油类型的参数,但保留了传统矿物三端元大类及混合类,去除了进一步细分的亚类。同时,用岩石热解滞留烃含量(S_1)代替了有机质丰度和成熟度指标,将页岩油划分为低含油、中等含油和高含油3类。另外,将地层压力系数小于0.8划分为异常低压、0.8~1.2划分为正常压力、大于1.2划分为异常高压,原油黏度不参与页岩油类型划分。依据研究划分方案给出了陆相页岩油一类、二类和三类甜点的定义,并分析讨论了中国典型陆相盆地代表性页岩油地层。期望利用该页岩油分类方案,进一步明确陆相页岩油甜点评价标准、认识甜点岩石类型、预测甜点分布特征以及更加准确计算页岩油资源量,从而简化实际勘探开发工作流程进而起到更好指导生产的作用。

关键词:压力系数;矿物成分;沉积构造;滞留烃S_1;地质甜点;资源评价;陆相页岩油

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Classification of lacustrine shale oil reservoirs in China and its significance

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Abstract: China has significant potential for the exploration of lacustrine shale oil, which serves as an important alternative resource for conventional oil and gas. However, the development and recovery of lacustrine shale oil face significant constraints due to the lack of fundamental research, unclear mechanisms of its formation and accumulation, and the absence of standardized criteria for evaluating "sweet spots". To address these issues, the authors proposed a set of simplified standards for lacustrine shale oil classification, taking into account previous research and the practical conditions of exploration and development. Based on the storage space and type of reservoir rocks, shale oil reservoirs

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are commonly classified into three major types, namely interbedded sand-shale, fractured shale, and pure shale, with the last type being taken as the focus of discussion in this paper. The pure shale type can be classified into laminated, bedded and massive shale oil reservoirs based on the sedimentary structure. Although the grain size was not taken as one of the parameters for shale oil classification, we kept the traditional three terminal element category and mixed category of minerals, and removed further subdivided subcategories; the Rock-Eval S_1 was used instead of TOC and R_o to divide shale oil reservoirs into three types: low oil content, medium oil content and high oil content; the formation pressure coefficient less than 0.8 is defined as abnormally low pressure, 0.8 ~ 1.2 is classified as normal pressure, and greater than 1.2 is classified as abnormally high pressure; the crude oil viscosity is not involved in the classification of shale oil reservoir types. In addition, this study designated type Ⅰ, Ⅱ and Ⅲ sweet spots, and discussed the representative types of shale oil reservoirs in typical continental basins in China. This paper enhances our understanding of the assessment standards, the type of rocks and the distribution of "sweet spots" in shale oil reservoirs. As a result, this research contributes to the advancement of shale oil exploration and development, providing valuable insights for future endeavors in this field.

Key words: pressure coefficient, mineralogical composition, sedimentary structure, residual hydrocarbon S_1, geologic sweet spot, resource assessment, lacustrine shale oil

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对于"页岩""页岩油"及"致密油"的概念,国内外长期以来没有形成统一意见,尤其是对"页岩油"与"致密油"的理解,不同学者之间存在较大差异[1-26]。这主要是中国学者与欧美学者对于"mud(泥)"的定义有差异,欧美学者一般将"泥"界定为粒径小于0.062 5 mm的沉积物,包括黏土级颗粒与粉砂级颗粒。在中国,"泥"的粒径对应黏土级颗粒即小于0.003 9 mm,粉砂的粒径在0.003 9 ~ 0.062 5 mm。在欧美国家,页岩定义为由黏土、泥、粉砂固结形成的具有层理、纹层状构造的岩石[27-28]。在中国的沉积岩石学教材中,泥岩被定义为由泥固结形成的岩石,呈块状,不含化石,页岩通常分层且易剥裂(易剥裂性是指分裂成薄片的特性),泥页岩指固结程度更高的泥岩[29]。最近修订的石油天然气行业标准(SY/T 5368—2016)中将粒径小于0.015 6 mm的碎屑颗粒含量大于或等于50 %的碎屑岩定义为泥岩。页岩是指具有页理构造的、黏土矿物含量大于50 %的沉积岩,颗粒粒径小于0.00 5 mm[14]。随着细粒沉积学的发展,结合勘探实践,页岩的概念不再受到岩石矿物组成的制约,由传统的黏土岩延伸至细粒沉积岩,甚至将碳酸盐矿物含量大于50 %的纹层状混积岩也称为页岩,例如美国鹰滩盆地白垩系混积岩层。国家标准《页岩油地质评价方法》(GB/T 38718—2020)定义页岩是一种具有页状或片状层理,粒径小于0.062 5 mm的细粒沉积岩。根据沉积环境的差异,可将页岩分为海相、陆相和海-陆过渡相。目前,中国对于页岩油的定义,有广义和狭义之分,狭义的页岩油是指富有机质泥页岩中自生自储型(源内)石油聚集;广义的页岩油泛指蕴藏在页岩层系中(包括页岩、致密砂岩以及碳酸盐岩等)源内以及近源聚集的石油资源[6,10,30]。与常规石油和致密油相比,页岩油藏具有以下特点:①未发生运移或发生了短距离运移,自生自储;②分布范围较广且不受构造高点控制,广泛发育在斜坡及洼陷区域;③资源丰度较低且储层致密,因此通常需要大规模实施人工储层改造才能实现经济效益开采[11,31]。

中国陆相页岩油资源潜力巨大,是实现国家原油增储上产的重要接替资源,也是保障国家能源安全的压舱石[1-22,30-31]。近年来,中国陆续在准噶尔盆地二叠系芦草沟组和风城组、鄂尔多斯盆地三叠系延长组7段、渤海湾盆地古近系沙河街组和孔店组、松辽盆地白垩系青山口组、四川盆地侏罗系大安寨组、江汉盆地古近系潜江组和新沟嘴组等主要陆相沉积盆地的一些典型富有机质页岩地层中取得了页岩油勘探突破[11,32-33]。但与美国海相页岩相比,中国陆相页岩具有横向连续性较差、热演化程度较低、地层能量较低等特点。而页岩油则具有原油黏度较大,其生产单井产量低、稳产周期短、且高产和低产井分布极不均匀、整体采收率偏低及经济效益差等特点[11,20]。由于陆相页

岩分布的非均质性特征,中国不同陆相盆地页岩油类型多样,到目前为止,各油田企业、各研究单位对于页岩油类型的划分仍不统一。不同学者根据陆相页岩油的沉积环境、相态、储层类型、热成熟度、岩性组合、源-储组合等参数指标对页岩油提出了多种分类方案(图1)。但由于考虑的因素不同,有些参数指标比较宽泛,对于页岩油资源评价、勘探部署、开发方案设计的指导性不强。笔者在综合分析前人研究方案的基础上,以简单实用为指导思想,主要依据岩石成分及其物理化学性质,包括矿物组分、沉积组构、岩性组合、生烃潜力及地层能量,建立了一套普适性较强的陆相页岩油分类评价标准,以期为中国陆相页岩油的勘探开发,特别是新一轮油气资源评价提供借鉴。

1　现存主要分类原则

目前,页岩分类的原则主要是基于岩石的成因。相比于海相页岩,陆相页岩具有更为丰富的岩石类型、产状及结构,更为多样的矿物种类与岩性组合关系,其分类方案长期处于百家争鸣的状态。尽管关于页岩油分类的原则有相同的趋势,但目前对陆相页岩油尚未形成统一的划分方案。为简化分类方案并增强其实用性,笔者重点考虑沉积构造、矿物成分、岩石热解滞留烃含量(S_1)及地压力系数等主要指标,它们基本上能够反应页岩的储集性、含油性、可压性、可动性等基本属性。黏土矿物含量与成熟度对可压性起关键作用,所以,简化起见,没有把可压性纳入分类指标。

1.1　沉积构造

姜在兴等认为页岩中常发育4种纹层,包括富有机质纹层、黏土纹层、碳酸盐纹层和富碎屑纹层,且其组合和比例不同,岩相也不同[9]。王勇等基于显微镜精细薄片观察,根据沉积纹层的厚度,将页岩划分为纹层状(纹层厚度<1 mm)、层状(纹层厚度>1 mm)和块状(纹层不发育)[33]。王勇等按照纹层类型进一步将沉积构造划分为水平纹层、波状纹层、透镜状纹层、交错纹层、粒序层理和冲刷面[34]。刘惠民等在综合考虑岩石矿物成分的基础上,结合沉积构造特征,包括夹层状、平直纹层、不平直纹层和块状构造,将渤海湾盆地东营凹陷沙河街组三段下亚段细粒沉积划分为11种不同岩相:①夹层灰岩;②平直纹层灰岩;③不平直纹层灰岩;④块状灰岩;⑤块状云岩;⑥平直纹层黏土岩;⑦块状黏土岩;⑧粉砂岩;⑨平直纹层混合岩;⑩不平直纹层混合岩;⑪块状混合岩[35]。由上述内容可知,沉积构造与结构类型复杂多样,基本属于定性描述,未建立统一的划分标准。

1.2　颗粒粒度与矿物成分

在陆相页岩类型划分中,颗粒粒度通常被划分为小于0.003 9 mm的泥级,0.003 9～0.062 5 mm的粉

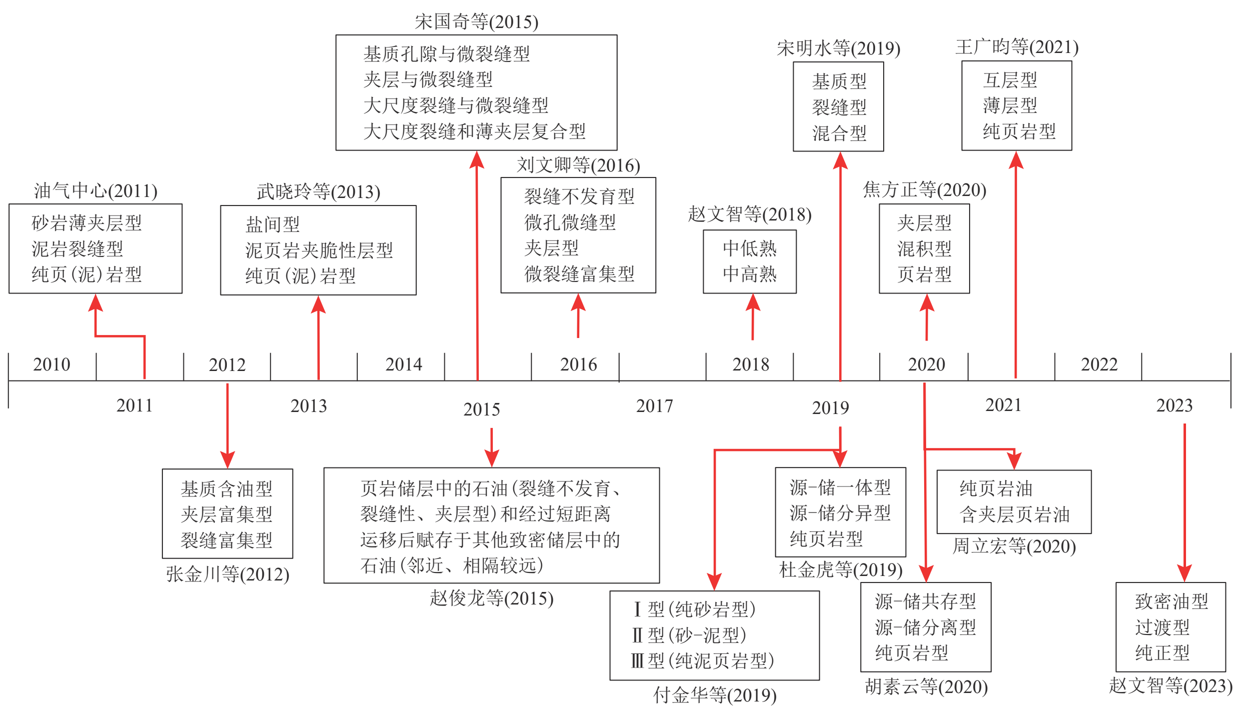


图1　中国陆相页岩油分类方案变化历程

Fig. 1　Evolution of classification scheme of lacustrine shale oil in China

砂级和大于0.062 5 mm的细砂级[30]。岩石颗粒粒度划分标准理论可行,但在实践应用中难度较大,尤其是进行定量分析,各个粒级百分含量难以准确测定。鉴于页岩粒度识别的困难,粒度+矿物成分的传统沉积岩命名方法在页岩分类中应用受到限制,因此需要用主要矿物成分作为识别端元进行分类,由于粒度与成分之间存在一定的相关性,粒度信息隐含在矿物组分中。

目前,较多学者按照传统岩石学命名方法,以长石+石英(长英质)矿物、黏土矿物和碳酸盐矿物为3个基本端元,以矿物含量50 %为岩石主名边界确定一级分区,划分为泥质岩、粉砂岩、灰云岩和混合岩4大类,再以25 %为界进行次一级分区,岩相类型为12种:①黏土质泥页岩;②粉砂质泥页岩;③灰质泥页岩;④粉砂岩;⑤泥质粉砂岩;⑥灰质粉砂岩;⑦灰云岩;⑧泥质灰云岩;⑨粉砂质灰云岩;⑩长英黏土质混合岩;⑪黏土碳酸盐质混合岩;⑫长英碳酸盐质混合岩(图2a)。实际应用操作难度较大[13, 32, 35]。也有部分学者,同样根据三大矿物的相对百分含量,以33 %和66 %为边界将页岩分为钙质泥岩、泥质灰岩、硅质灰岩、泥质泥页岩和硅质泥岩5大类岩相(图2b)[36]。此外,黎茂稳等[32]还根据全岩矿物组成进行了有机相划分,具体分类方案请参考图2c和对应文献[32]。另外,有学者将特殊的沉积环境纳入分类,例如,吉木萨尔凹陷芦草沟组页岩沉积形成于受机械搬运、化学沉淀以及生物作用控制的咸化湖盆,其矿物组成有其复杂性和特殊性,除了陆源碎屑,还有内碎屑、少量火山灰以及自生碳酸盐、硫酸盐、硅酸盐、黄铁矿和黏土矿物。因此,蒽克来等[37]和王小军等[38]进一步按照陆源碎屑、火山物质和内源化学物质三端元法将芦草沟组页岩划分为陆源碎

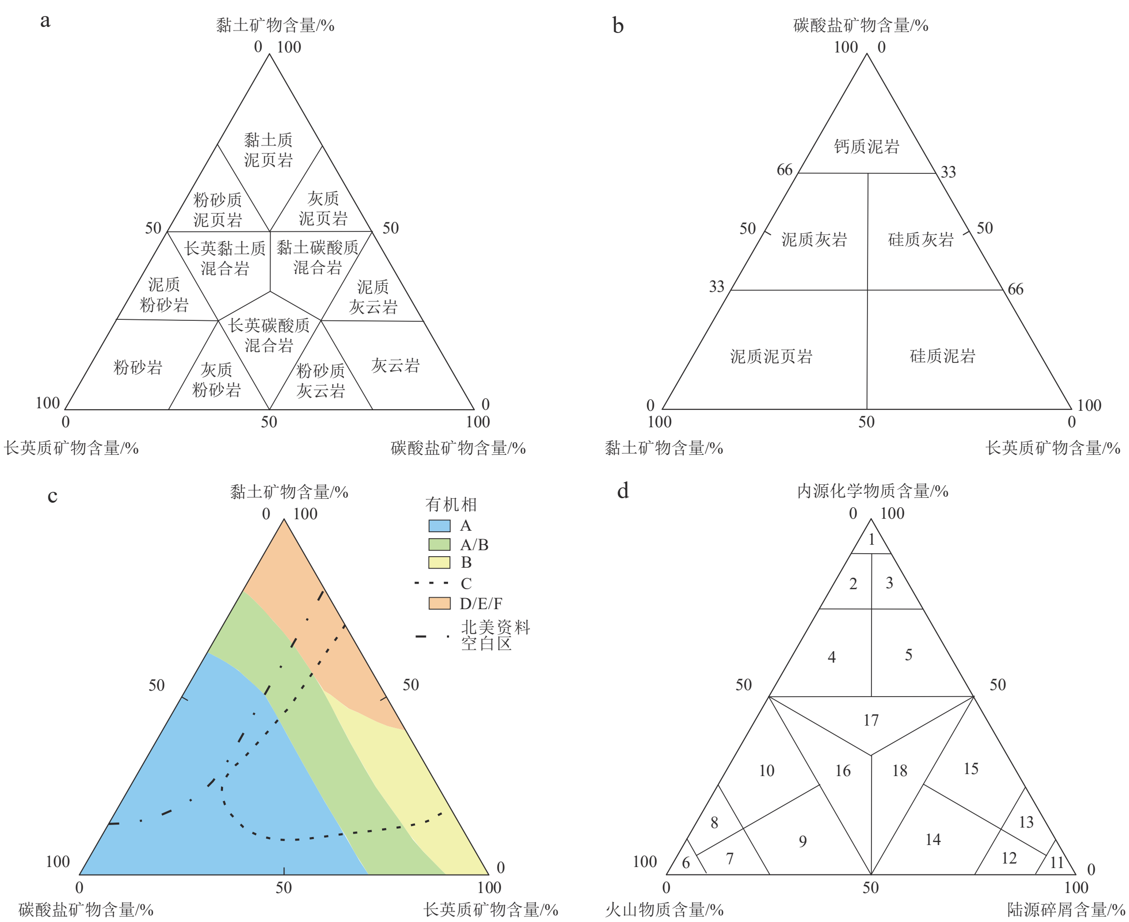


图2 基于矿物组分的岩相分区方案(修改自文献[13, 32, 36, 38])

Fig. 2 Petrographic classification scheme based on mineral composition (modified after [13, 32, 36, 38])

1. 内源沉积岩;2. 含凝灰内源沉积岩;3. 含(粉)/泥内源沉积岩;4. 凝灰质内源沉积岩;5.(粉)砂质/泥质内源沉积岩;6. 凝灰岩;7. 含(粉)砂/泥沉凝灰岩;8. 含内源沉积沉凝灰岩;9.(粉)砂/泥质沉凝灰岩;10. 内源沉积质沉凝灰岩;11.(粉)砂岩/泥岩;12. 含凝灰(粉)砂岩/泥岩;13. 含内源沉积(粉)砂岩/泥岩;14. 凝灰质(粉)砂岩/泥岩;15. 内源沉积质(粉)砂岩/泥岩;16. 火山碎屑型混积岩;17. 碳酸盐型混积岩;18. 陆源碎屑型混积岩

a. 先以50 %为边界确定岩石主名,再以矿物含量25 %为界进行二级分区;b. 分别以33 %,50 %和66 %为边界确定岩相类型;c. 全岩矿物和有机岩相综合划分;d. 基于陆源碎屑、火山物质和内源化学物质类型划分

屑岩类、碳酸盐岩类、火山碎屑岩类和正混积岩类4大类18小类(图2d)。由此可见,基于岩石矿物成分划分页岩类型的方案繁多复杂,且标准不一,在实际生产中难以严格按照该标准开展工作。不同盆地不同地层矿物组成差异较大,中国典型陆相盆地6套页岩地层矿物组成如图3所示。

1.3 有机质含量和成熟度

前人按照有机质的丰度(总有机碳含量*TOC*)将页岩划分为多个不同的岩相。张金川等将有机质含量作为页岩油选区的标准之一,*TOC*>0.5 %的区域为远景区,*TOC*>1.0 %的区域为有利区,*TOC*>2.0 %的区域为页岩油勘探的目标区[18]。姜在兴等建议以2.0 %和4.0 %作为*TOC*的界限划分出低、中、高有机质页岩[61]。王勇等依据产油井有机质丰度(*TOC*)普遍大于或等于2 %,将页岩划分为富有机质(*TOC*≥2 %)和含有机质(*TOC*<2 %)两大类[34]。Liu等(2019)分别以*TOC*等于1 %和2 %为界限将页岩划分为贫有机质(*TOC*<1 %)、中等含量有机质(1 %≤*TOC*≤2 %)和富有机质页岩(*TOC*>2 %)[62]。金之钧等根据有机质含量将陆相页岩划分为差(*TOC*<1 %)、中(1 %≤*TOC*≤2 %)、好(*TOC*>2 %)3类[11]。黎茂稳等分别以*TOC*为0.5 %,1.0 %,2.0 %和4.0 %作为界限将页岩划分为含碳(*TOC*<0.5 %)、低碳(0.5 %≤*TOC*≤1.0 %)、中碳(1.0 %<*TOC*<2.0 %)、高碳(2.0 %≤*TOC*≤4.0 %)和富碳(*TOC*>4.0 %)页岩[32]。彭军等结合东营凹陷南坡陈官庄地区古近系沙河街组细粒混合沉积特征与勘探开发现状,以有机质含量1 %和2 %作为界限,将细粒沉积划分为贫有机质(*TOC*<1 %)、含有机质(1 %≤*TOC*≤2 %)和富有机质(*TOC*>2 %)[63]。由此可见,基于*TOC*对页岩油类型划分并未形成统一的意见。尽管有机质是形成石油的物质基础,其含量也在一定程度上影响储层质量,*TOC*与页岩油产出效果之间的关系依然模糊不清。

杜金虎等[1]、胡素云等[8]、赵文智等[19]认为,陆相页岩油的资源潜力主要取决于陆相页岩层系中尚未转化有机质的生烃潜力和已生成尚未排出的滞留液态烃的数量,陆相页岩油类型的划分主要依据有机质丰度和成熟度这两个参数,可划分为中低成熟度(R_o为0.5 %~1.0 %)和中高成熟度(R_o为1.0 %~1.5 %)页岩油两大类型。考虑组构特征及源储组合关系,可将中高成熟度页岩分为源-储一体型、源-储分异型和纯页岩型[1]。付锁堂等[6]和金之钧等[11]依据有机质热演化程度(镜质体反射率R_o)将中国陆相页岩油资源分成

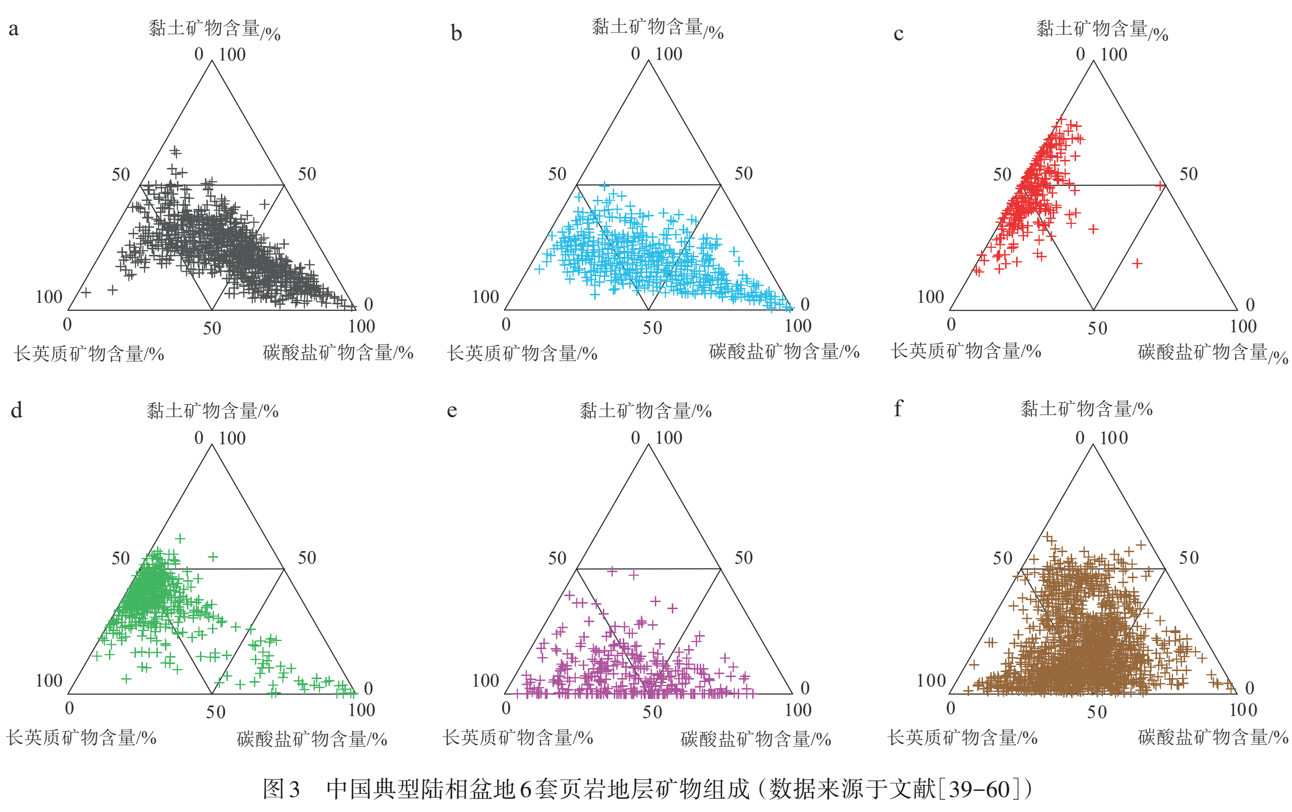


图3 中国典型陆相盆地6套页岩地层矿物组成(数据来源于文献[39-60])

Fig. 3 Mineral composition of six shale sequences in typical lacustrine basins of China (data were collected from [39-60])

a. 渤海湾盆地沙河街组;b. 渤海湾盆地孔店组;c. 鄂尔多斯盆地延长组7段;d. 松辽盆地青山口组;e. 准噶尔盆地芦草沟组;f. 准噶尔盆地风城组

了两大类，即中低成熟度（R_o≤0.9 %）和中高成熟度（R_o>0.9 %）页岩油；但金之钧等[11]指出，中低与中高成熟度的界限值R_o（0.8 %，0.9 %或1.0 %）仍需进一步研究。值得注意的是，中国已经在R_o为0.7 %的陆相页岩地层取得了页岩油勘探的突破。因此，中低与中高成熟度的界限值依然是个值得商榷的问题。根据油田实际生产数据，S_1在某种程度上是一个比*TOC*更好使用的参数，S_1大于4 mg/g的页岩大部分已经取得较好的单井产量，韩文中等（2021）[64]和赵贤正等（2023）[65]按照1 mg/g≤S_1<2 mg/g，2 mg/g≤S_1<4 mg/g和S_1≥4 mg/g将页岩油划分为Ⅰ，Ⅱ和Ⅲ类，与本研究观点较为一致。

1.4 原油黏度及压力系数

原油的黏度是影响页岩油开发的关键因素之一，原油黏度越低，其流动越容易，开采的难度也相对更小。不同地层页岩油黏度差异较大，其数值可由鄂尔多斯盆地长7段的1.21 ~ 1.96 mPa·s[66-67]至准噶尔盆地吉木萨尔凹陷芦草沟组的数百（407.08 mPa·s）[11]。原油的化学组成是控制其黏度的内在因素，原油的分子量越大，其黏度越高[68]。冯国奇等[69]通过研究发现，南襄盆地泌阳凹陷页岩油中胶质沥青的含量随着埋藏深度的增加逐渐减小，饱和烃的相对含量则逐渐增加，使得原油黏度随着埋深增加而减小。地层温度是影响原油黏度的外在因素，温度越高，原油黏度越低。此外，石油中溶解气的含量对原油的黏度也有一定的影响，溶解气含量越高，原油黏度越低。陈佳伟[70]将页岩油黏度低于10 mPa·s作为页岩油可动的标准之一。值得注意的是，实际地层条件下的原油黏度表征还存在着一定的困难，且依赖的因素较多，目前关于黏度的划分并未形成统一标准，因此不考虑其作为划分参数。

地层压力系数反映地层能量大小，决定着原油的采出效果。地层压力系数越大，油气开采过程中的驱动力越强，页岩油可动性越好，油气井产量也越高[71-77]。中国典型陆相盆地6套页岩地层压力、压力系数与深度相关关系可直观反映页岩油藏所在深度段地层能量的大小（图4，图5）。因此，地层压力系数在页岩油可动资源量和甜点评价方面可以作为一个重要参数。但在目前页岩油的分类方案中，地层压力系数并没有很好地被运用。

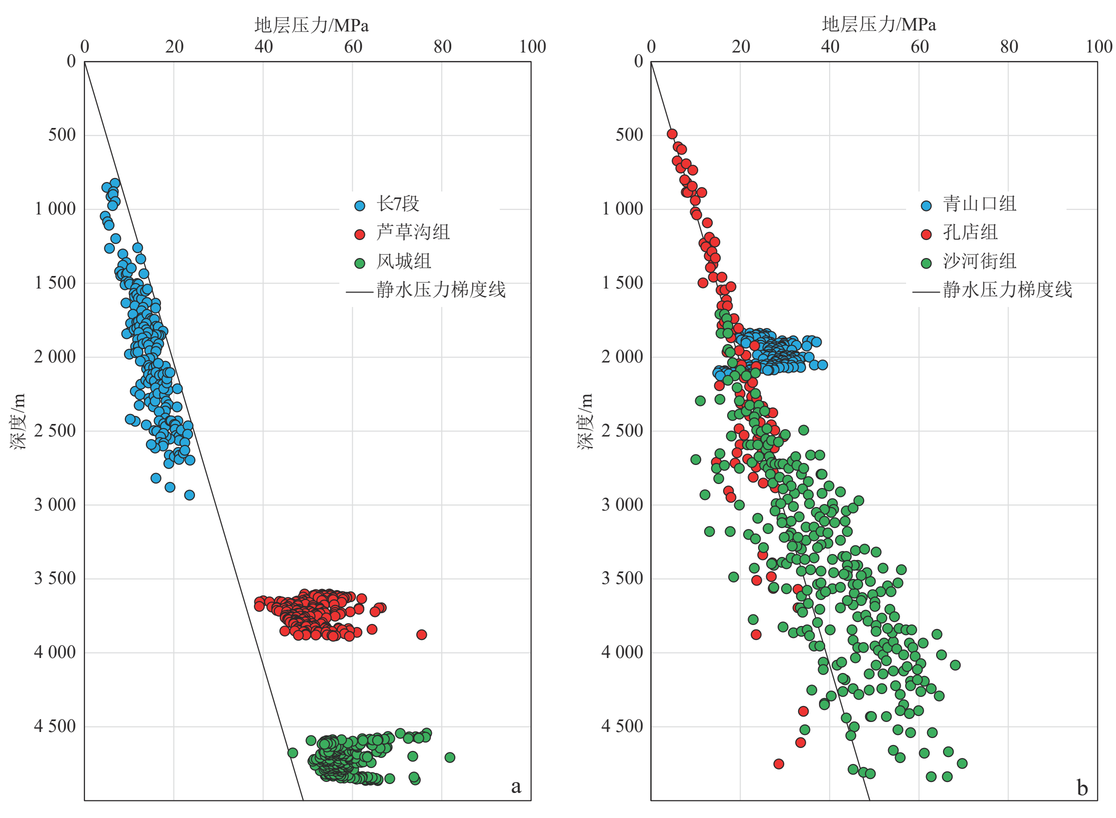


图4 中国典型陆相盆地6套页岩地层压力与深度的关系（数据来源于文献[71-77]）

Fig. 4 Correlation between pressure and depth of six shale sequences in typical lacustrine basins of China (data were collected from [71-77])

a. 鄂尔多斯盆地延长组7段、准噶尔盆地芦草沟组和风城组；b. 松辽盆地青山口组、渤海湾盆地孔店组和沙河街组

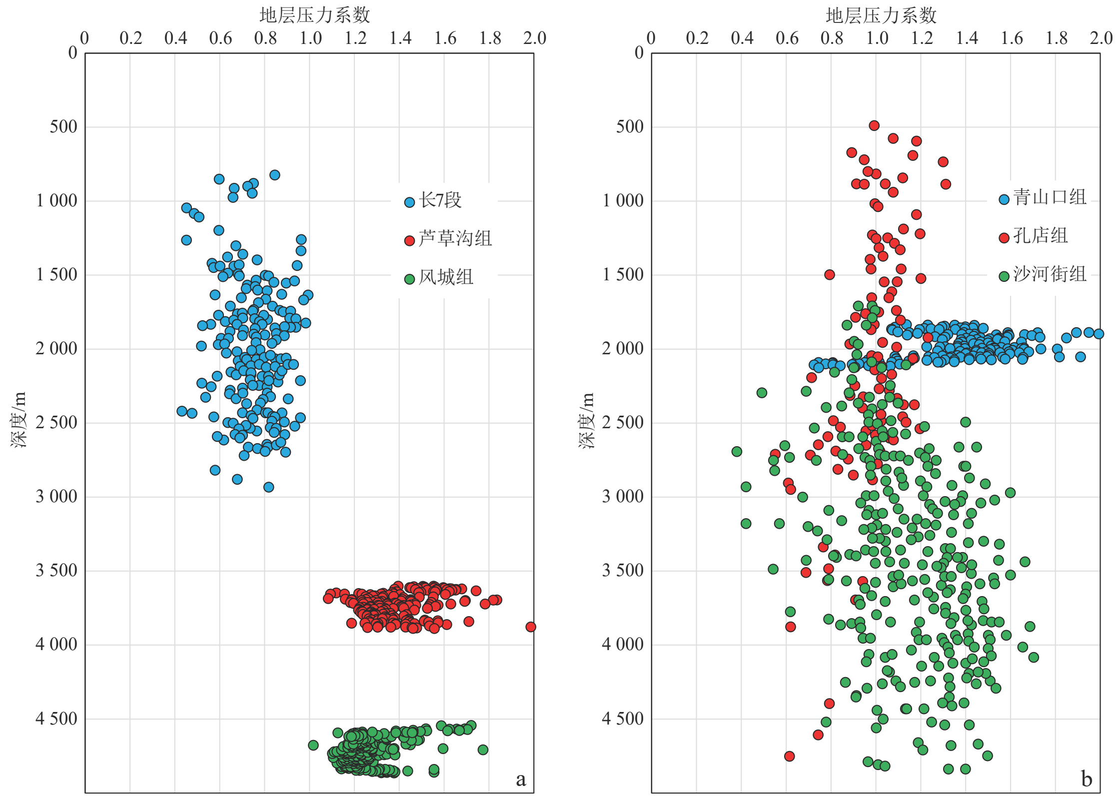


图5 中国典型陆相盆地6套页岩地层压力系数与深度的关系(数据来源于文献[71-77])

Fig. 5 Correlation between pressure coefficient and depth of six shale sequences in typical lacustrine basins of China (data were collected from [71-77])

a. 鄂尔多斯盆地延长组7段、准噶尔盆地芦草沟组和风城组;b. 松辽盆地青山口组、渤海湾盆地孔店组和沙河街组

2 分类方案及典型实例

2.1 分类方案

根据页岩油赋存空间和储集岩石类型的差异,可将页岩油划分为夹层型、裂缝型和纯页岩型。本文不对夹层型和裂缝型页岩油展开讨论,重点以纯页岩型页岩油为例讨论分类方案。在考虑沉积构造和矿物成分的基础上,结合油田实际生产中影响页岩油产出的主要因素,加入岩石热解滞留烃S_1和地层压力系数对纯页岩型页岩油开展科学系统的分类。

依据上述分类的原则,本研究提出分类方案(表1)及步骤如下:

1) 根据页岩沉积构造特征,将纹层厚度<1 mm的划分为纹层状页岩,1 mm≤纹层厚度≤10 mm的划分为层状页岩,纹层厚度>10 mm的划分为块状页岩。岩石颗粒粒径不参与本研究中页岩油类型划分。

2) 根据岩石的矿物组成及成因,保持传统的以长石+石英(长英质)矿物、黏土矿物和碳酸盐岩矿物为3个基本端元的分类方案不变。以矿物含量50 %为界确定岩石的基本名称,不再将岩石进一步细分。按照混积岩的定义,长石+石英(长英质)矿物、黏土矿物和碳酸盐矿物中每一种组分的含量均不超过50 %。因此,基于岩石矿物组成可以将页岩划分为黏土质、长英质、灰云质和混合质4种基本类型。

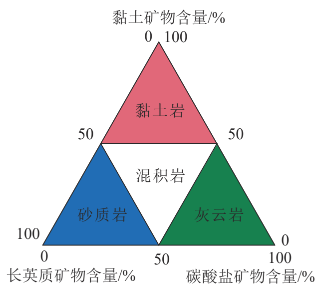
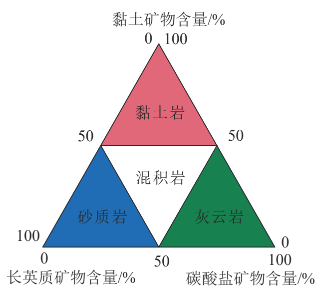
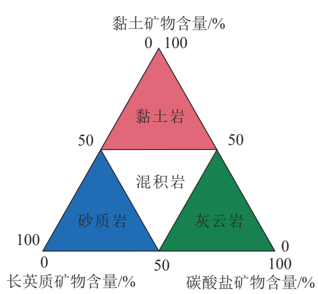
3) 根据岩石热解滞留烃含量S_1,将S_1<2 mg/g的划分为低含油,2 mg/g≤S_1≤4 mg/g的划分为中等含油,S_1>4 mg/g的划分为高含油。考虑到滞留烃的含量实际上是对有机质含量和成熟度的综合反映,因此,有机质的含量和成熟度不参与本研究中页岩油类型划分。值得注意的是,由于取心条件及实验分析及时性,轻烃散逸会造成S_1偏低,建议通过密闭取心且现场热解或冷冻取心后实验室测试获取该参数。

4) 根据地层压力系数(即地层能量),将压力系数<0.8的页岩油藏划分为异常低压油藏,将0.8≤压力系数≤1.2的页岩油藏划分为常压油藏,将压力系数>1.2的页岩油藏划分为异常高压油藏。原油黏度不参与本研究中页岩油类型划分。

根据上述分类方案,提出命名原则:沉积构造+矿

表1 中国陆相页岩油分类方案

Table 1 Classification schemes of lacustrine shale oil reservoirs in China

<table>
<tr><th>页岩油类型</th><th>沉积构造</th><th>矿物组成</th><th>岩石热解滞留烃含量S_1/(mg/g)</th><th>地层压力系数</th><th>典型实例</th></tr>
<tr><td>夹层型</td><td></td><td></td><td></td><td></td><td>长7段</td></tr>
<tr><td>裂缝型</td><td></td><td></td><td></td><td></td><td>风城组</td></tr>
<tr><td rowspan="27">纯页岩型</td><td rowspan="9">纹层状</td><td rowspan="9">
</td><td rowspan="3"><2</td><td><0.8</td><td></td></tr>
<tr><td>0.8～1.2</td><td></td></tr>
<tr><td>>1.2</td><td></td></tr>
<tr><td rowspan="3">2～4</td><td><0.8</td><td>长7段</td></tr>
<tr><td>0.8～1.2</td><td>沙河街组、孔店组、长7段</td></tr>
<tr><td>>1.2</td><td>沙河街组、青山口组</td></tr>
<tr><td rowspan="3">>4</td><td><0.8</td><td></td></tr>
<tr><td>0.8～1.2</td><td>沙河街组</td></tr>
<tr><td>>1.2</td><td>沙河街组</td></tr>
<tr><td rowspan="9">层状</td><td rowspan="9">
</td><td rowspan="3"><2</td><td><0.8</td><td></td></tr>
<tr><td>0.8～1.2</td><td></td></tr>
<tr><td>>1.2</td><td></td></tr>
<tr><td rowspan="3">2～4</td><td><0.8</td><td></td></tr>
<tr><td>0.8～1.2</td><td>沙河街组、孔店组</td></tr>
<tr><td>>1.2</td><td>沙河街组、青山口组</td></tr>
<tr><td rowspan="3">>4</td><td><0.8</td><td></td></tr>
<tr><td>0.8～1.2</td><td>沙河街组、孔店组</td></tr>
<tr><td>>1.2</td><td>沙河街组</td></tr>
<tr><td rowspan="9">块状</td><td rowspan="9">
</td><td rowspan="3"><2</td><td><0.8</td><td></td></tr>
<tr><td>0.8～1.2</td><td>风城组</td></tr>
<tr><td>>1.2</td><td>芦草沟组、风城组</td></tr>
<tr><td rowspan="3">2～4</td><td><0.8</td><td></td></tr>
<tr><td>0.8～1.2</td><td>风城组</td></tr>
<tr><td>>1.2</td><td>芦草沟组、风城组、青山口组</td></tr>
<tr><td rowspan="3">>4</td><td><0.8</td><td></td></tr>
<tr><td>0.8～1.2</td><td></td></tr>
<tr><td>>1.2</td><td></td></tr>
</table>

物成分+含油级别+地层压力特征。例如，纹层状长英质高含油异常高压页岩油藏。基于该分类方案，纯页岩型页岩油理论上4个参数总共有108种组合关系，但在实际勘探中遇到的类型数量是一定的，因此，本文重点讨论中国4个典型盆地6套代表性地层的页岩油特点及类型。

2.2 甜点分级

根据本研究提出的分类方案，进一步将页岩油甜点划分为一类、二类和三类3个等级。

2.2.1 一类甜点

一类甜点是最有利的页岩油勘探目标，具有最优的沉积构造、矿物组成、含油级别和地层压力，即本研究分类方案中的任一指标均是最优。例如，具有纹层状和层状构造、岩石组成以长英质矿物、灰云质矿物和混合质矿物为主、S_1>4 mg/g、地层压力系数>1.2的页岩油均属于一类甜点。组合形式包括：①纹层状长英质高含油高压页岩油藏；②纹层状灰云质高含油高压页岩油藏；③纹层状混合质高含油高压页岩油藏；④层状长英质高含油高压页岩油藏；⑤层状灰云质高含油高压页岩油藏；⑥层状混合质高含油高压页岩油藏。在当前技术条件下开发成本在50美元/bbl左右。

2.2.2 二类甜点

二类甜点是次一级有利的页岩油勘探目标，具有良好的沉积构造、矿物组成、含油性和地层能量组合特点，即本研究分类方案中的某一项指标非最优。例如，

①具有纹层状和层状构造、岩石组成以长英质矿物、灰云质矿物和混合质矿物为主、2mg/g≤S_1≤4 mg/g、地层压力系数>1.2；②具有纹层状和层状构造、岩石组成以长英质矿物、灰云质矿物和混合质矿物为主、S_1>4 mg/g、0.8<地层压力系数<1.2；③具有块状构造、岩石组成以长英质矿物、灰云质矿物和混合质矿物为主、2mg/g≤S_1≤4 mg/g、地层压力系数>1.2的页岩油均属于二类甜点。典型的组合形式包括但不限于：①纹层状长英质中等含油高压页岩油藏；②纹层状灰云质高含油常压页岩油藏；③纹层状黏土质高含油高压页岩油藏；④层状长英质中等含油高压页岩油藏；⑤层状灰云质中等含油高压页岩油藏；⑥层状混合质高含油常压页岩油藏。由于二类甜点组合类型多样，此处不一一列出页岩油类型。在当前技术条件下开发成本在60美元/bbl左右。

2.2.3　三类甜点

三类甜点是再次一级有利的页岩油勘探目标，具有较好的沉积构造、矿物组成、含油性和地层能量组合特点，即本研究分类方案中的某两项指标非最优。例如，①具有纹层状和层状构造、岩石组成以长英质矿物、灰云质矿物和混合质矿物为主、2 mg/g≤S_1≤4 mg/g、0.8<地层压力系数<1.2；②具有纹层状和层状构造、岩石组成以黏土矿物为主、2 mg/g≤S_1≤4 mg/g、地层压力系数>1.2；③具有块状构造、岩石组成以黏土矿物为主、S_1>4 mg/g、地层压力系数>1.2的页岩油均属于三类甜点。典型的组合形式包括但不限于：①纹层状长英质中等含油常压页岩油藏；②纹层状灰云质中等含油常压页岩油藏；③纹层状黏土质高含油常压页岩油藏；④层状长英质中等含油常压页岩油藏；⑤层状灰云质中等含油常压页岩油藏；⑥层状混合质中等含油常压页岩油藏。同样地。由于三类甜点组合类型多样，此处不一一列出页岩油类型。在当前技术条件下开发成本在70美元/bbl左右。

2.3　典型实例

2.3.1　渤海湾盆地古近系沙河街组和孔店组

沙河街组形成于断陷咸化湖盆半深湖-深湖沉积环境，有机质含量高，分布范围广，在东营、沾化、车镇和惠民等凹陷均有分布，页岩油主要分布于沙河街组四段上亚段（沙四上亚段）、沙三下亚段及沙一段3套烃源岩层中，厚度可达300 ~ 500 m，以东营凹陷和沾化凹陷为主[78-79]。沙河街组页岩纹层厚度较小，主要分布在50 ~ 100 μm和1 ~ 5 mm，属于典型的纹层状和层状页岩（图6a，b）[35]。该页岩组成主要包括混

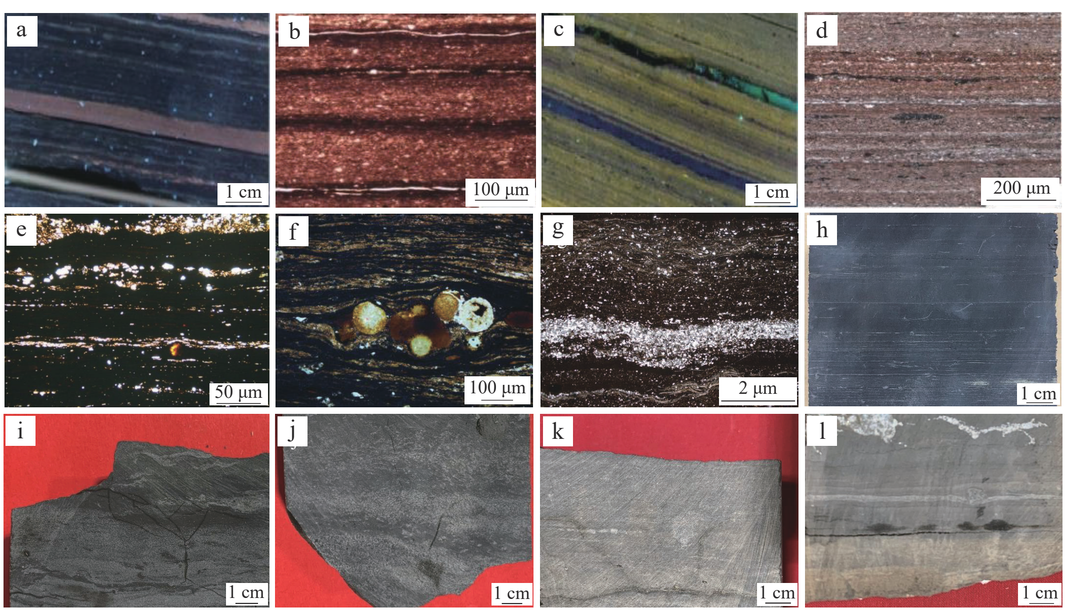


图6　中国典型陆相盆地6套页岩地层沉积构造特征

Fig. 6　Characteristics of sedimentary structure of six shale sequences in typical lacustrine basins of China

a. 房39X1井，沙河街组，埋深4 372.05 m，镜下照片；b. 房39X1井，沙河街组，埋深4 372.05 m，镜下照片；c. 官19-25井，孔店组，埋深3 347.08 m，镜下照片；d. 官19-25井，孔店组，埋深3 347.08 m，镜下照片；e. 瑶页1井，长7段，埋深226.00 m，镜下照片；f. 瑶页1井，长7段，埋深226.00 m，镜下照片；g. 古页3HC井，青山口组，埋深2 450.20 m，镜下照片；h. 古页3HC井，青山口组，埋深2 494.70 m，岩心照片；i. 玛页1井，风城组，埋深4 641.09 m，岩心照片；j. 玛页1井，风城组，埋深4 643.53 m，岩心照片；k. J10025井，芦草沟组，埋深3 275.43 m，岩心照片；l. J10025井，芦草沟组，埋深3 723.43 m，岩心照片

合质和灰云质矿物以及部分长英质矿物，黏土矿物含量较低（图3）。沙河街组页岩中滞留烃含量总体较高，主要介于1.2 ~ 5.4 mg/g，均值为3.8 mg/g，最大可达16.5 mg/g（图7），属于中等含油和高含油页岩油藏。该地层压力范围较大（图8），压力系数主要介于0.8 ~1.2（图5），但总体上高于静水柱压力（图4），可划分为正常压力和异常高压页岩油藏。综上所述，沙河街组页岩油可定名为纹层状（层状）混合质（灰云质）中等含油（高含油）正常压力（异常高压）页岩油藏。

孔店组（主要为二段，简称孔二段）为一套富有机质厚层泥页岩，主要分布在沧东凹陷和黄骅凹陷，沉积形成于湖盆初始裂陷期，孔二段沉积期为闭塞湖盆且此时为最大湖泛面，整体处于偏咸化的还原环境[80-81]。该地层纹层发育，赵贤正等（2023）[65]研究表明，岩心连续扫描统计的平均纹层密度为330层/m，单一纹层厚度约3 mm，而荧光薄片统计的平均纹层密度可达11 000层/m，单一纹层厚度约0.05 ~ 0.50 mm [65]。由此可见，孔店组页岩属于纹层状和层状页岩（图6c，d）。孔店组页岩岩石组成以混合质、长英质和灰云质矿物为主（图3）。岩石含油量高，S_1总体上介于3.7 ~ 7.0 mg/g，平均值为5.3 mg/g（图7），可划分为高含油页岩油藏。孔店组地层压力与静水柱压力相当（图4），异常压力不明显[82]，压力系数主要分布在0.8 ~ 1.2（图5，图8），属于典型的正常压力页岩油藏。综上所述，孔店组页岩油可定名为纹层状（层状）混合质（长英质和灰云质）高含油正常压力页岩油藏。

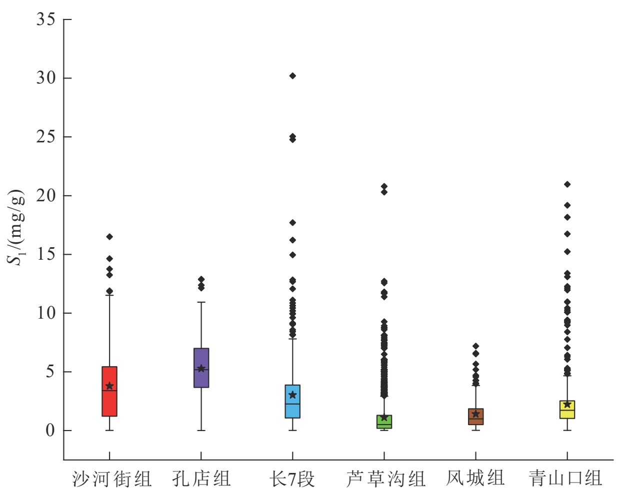


图7　中国典型陆相盆地6套页岩滞留烃含量特征（数据来源于文献[51-53，64，83-137]）

Fig. 7　Characteristics of residual hydrocarbon content in six shale sequences in typical lacustrine basins of China (data were collected from [51-53, 64, 83-137])

2.3.2　鄂尔多斯盆地三叠系延长组7段

延长组7段（长7段）页岩形成于持续沉降的坳陷湖盆，其沉积时期是湖盆发育的鼎盛时期，湖泊面积最大，半深湖-深湖区发育广泛分布的优质烃源岩[138]。长7段页岩自上而下细分为长7^1、长7^2和长7^3共3个亚段，其中长7^1亚段和长7^2亚段为夹层型页岩，长7^3亚段为主力烃源岩，为页岩油勘探提供了有利的地质条件。长7段富有机页岩纹层十分发育[4]，蒽克来（2020）[139]认为该层段纹层类型包括富凝灰质纹层、富有机质纹层、粉砂级长英质纹层和黏土纹层，纹层厚度在100 ~ 1 000 μm不等，属于典型的纹层状页岩（图6e，f）。长7段富有机页岩以长英质矿物和黏土矿物为主，还包括部分混合质矿物，云灰质矿物含量总体较低（图3）。该页岩含油量差异极大，S_1主要介于1.1 ~ 3.9 mg/g，平均值为3.0 mg/g，最大值可达30.2 mg/g（图7），可划分为中等含油页岩油藏。长7段页岩地层压力较低，低于静水柱压力（图4），压力系数主要介于0.6~1.0（图5，图8），可划分为异常低压和正常压力页岩油藏。综上所述，长7^1亚段和长7^2亚段为夹层型页岩，长7^3亚段页岩油可定名为纹层状长英质（黏土质/混合质）中等含油异常低压（正常压力）页岩油藏。

2.3.3　准噶尔盆地中二叠统芦草沟组和下二叠统风城组

芦草沟组形成于典型的咸化湖盆，受机械沉积、化学沉积、生物沉积等多种作用共同控制。芦草沟组优

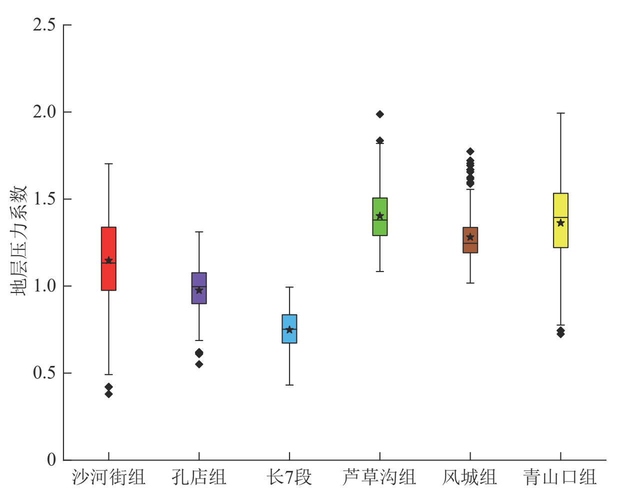


图8　中国典型陆相盆地6套页岩地层压力系数特征（数据来源于文献[71-77]）

Fig. 8　Characteristics of pressure coefficients of six shale sequences in yypical lacustrine basins of China (data were collected from [71-77])

质烃源岩分布面积广、沉积厚度大,广泛发育富有机质油页岩、灰黑色泥岩和灰黑色白云质泥岩,总体表现为源–储一体和近源成藏的特点,为准噶尔盆地页岩油的勘探创造了良好的地质条件[37-38]。芦草沟组页岩粒度较细,粒径大多小于0.5 mm,细粉砂岩、碳酸盐岩和泥岩呈厘米级互层分布[38]。因此,根据本研究分类方案,芦草沟组页岩的沉积构造为块状(图6k,l)。大量统计数据表明,芦草沟组页岩岩石组成以长英质矿物和碳酸盐岩矿物为主,黏土含量较低,也有较大一部分岩石矿物组成为混合成因(图3)。芦草沟组页岩中滞留烃的含量总体较低,S_1平均值仅有1.1 mg/g,大多低于5 mg/g,部分样品S_1值较大,最大可达20.8 mg/g(图7),总体属于低含油和中等含油。值得注意的是,该地层流体压力较高,远高于静水柱压力(图4),地层压力系数总体上介于1.2~1.8(图5,图8),属于典型的高压页岩油藏。综上所述,芦草沟组页岩油可定名为块状长英质(灰云质)低含油(中等含油)异常高压页岩油藏。

风城组形成于碱湖环境,受机械、化学、生物和火山等作用控制,平面分布面积约5 000 km^2,沉积厚度多在150~1 000 m,局部地区可达1 800 m,是该凹陷的主力烃源岩[22,140]。由于其沉积环境的特殊性,风城组页岩碱性矿物含量较高,以火山碎屑岩、灰质泥岩、云质碎屑岩、灰质砂岩和厚层泥岩为主[140]。沉积构造呈纹层状与薄纹层状、薄互层状,厚度一般在厘米级到毫米级[22],属于层状页岩或块状页岩(图6i,j)。风城组页岩矿物组织主要包括混合质、长英质和云灰质矿物(图3)。该地层滞留烃含量总体上略高于芦草沟组,S_1平均值为1.4 mg/g,整体偏低,最高为7.2 mg/g,总体介于低含油和中等含油(图7)。该地层压力较高,高于静水柱压力(图4),地层压力系数主要介于1.1~1.6(图5,图8),属于正常压力和异常高压页岩油藏。综上所述,风城组页岩油可定名为层状(块状)混合质(长英质和灰云质)低含油(中等含油)异常高压(正常压力)页岩油藏。此外,风城组页岩中裂缝发育,裂缝是该地层中最主要的储集空间[141],因此,风城组页岩油也属于裂缝型页岩油藏。

2.3.4　松辽盆地青山口组

青山口组页岩形成于温暖潮湿条件下的湖泊沉积,沉积水体为半深湖–深湖还原环境,为页岩中有机质的形成和富集提供了有利的地质条件[36]。青山口组页岩不同岩相纹层厚度差异较大,高有机质纹层状层理厚度小于1 mm、大于1 mm和大于10 mm均有发育[36, 142-144],可划分为纹层状、层状和块状页岩(图6g,h)。该页岩岩石组成以长英质矿物和混合质矿物为主,黏土矿物含量整体较高,主要分布在25%~50%,部分样品碳酸盐矿物含量较高(图3),属于长英质和混合质页岩。青山口组页岩滞留烃含量差异较大,S_1主要介于1.0~2.5 mg/g,平均值为2.2 mg/g,最高可达21.0 mg/g(图7),可划分为中等含油页岩油藏。该页岩地层压力范围较大,总体上高于静水柱压力(图4),压力系数主要介于1.2~1.8(图5,图8),可划分为异常高压页岩油藏。综上所述,青山口组页岩油可定名为纹层状(层状和块状)长英质(混合质)中等含油异常高压页岩油藏。

3　分类意义

长期勘探开发实践表明,页岩油勘探的关键在于甜点预测与有利区带优选,而准确地计算页岩油资源量可以有效降低勘探风险。针对中国陆相页岩油进行合理分类具有以下5个方面的意义。

1) 明确甜点评价标准。甜点评价是页岩油气勘探开发中的重点内容之一,是对生烃特性、岩性、物性、含油性和力学性质等属性的综合评价。由于其内涵不断扩展,评价参数的选取以及参数的取值可能需要随着不同地层和不同盆地进行调整[46]。因此,截至目前,关于甜点的评价标准仍没有达成一致的认识。在全面了解和掌握现有数据及资料的基础上,对中国陆相页岩油进行科学系统的分类有助于进一步明确甜点的评价标准。

2) 认识甜点岩石类型。中国陆相页岩油富集机理不清,不同类型的岩石中页岩油的富集机理和条件各不相同。此前的甜点主要从储层物性的角度考虑,对其形成条件和控制因素未做出深入分析,岩相类型多变的陆相页岩储层需要更高的刻画精度。因此,进一步深入认识构成页岩油甜点的岩石类型对于精细勘探具有重要意义。

3) 预测甜点分布特征。陆相页岩非均质性极强,其厚度在平面上的连续性较差,其岩相在纵向上变化较快,在明确甜点评价标准和认识甜点岩石类型的基础上,结合页岩层系形成的沉积环境特征、所处的地质构造背景以及岩性组合特点,对陆相页岩油进行系统科学的分类有助于分析优质储集层的时空分布规律,从而预测甜点的分布特征,对页岩油井位部署意义重大。

4) 准确计算页岩油资源量。相比于独立分布的常规油气藏,页岩油气通常呈大面积连续分布,故而也

被称之为连续型油气藏。因此,基于常规油气藏规模和油气数量的资源评价方法不能直接用于页岩油气资源评价。过高或者过低判断页岩油资源潜力都会给页岩油勘探带来巨大的风险,精细的分类可以更加准确地评价页岩油资源量并且有效地指导生产。

5)分级开发油气资源。油气资源分级开发在本文中是指在现有的技术条件下优先开采可动用性强的油气资源,例如,中高成熟度含碳纹层型碎屑质粉-细砂岩低黏度异常高压页岩油藏可通过水平井和水力压裂技术开采,而中-低熟含碳纹层型碎屑质泥页岩低黏度异常低压油藏则可能需要借助于原位改质技术才能进行开发[145]。因此,对中国陆相页岩油进行科学系统分类可实现油气资源最大限度开发利用,切实保障国家能源安全。

4 结语

关于中国陆相页岩油分类的原则及标准,在前人工作的基础上,笔者坚持以沉积构造、矿物组成、S_1、地层压力系数作为页岩油分类的基本原则,以纹层厚度1 mm和10 mm为界将纯页岩型页岩油划分为纹层状、层状和块状;以矿物含量50 %为界作为区分长英质、黏土质、灰云质和混合质岩石的标准;以S_1数值2 mg/g和4 mg/g为界将含油级别分为低含油、中等含油和高含油3种类型;以地层压力系数数值0.8和1.2为界将页岩油划分为异常低压、正常压力和异常高压页岩油藏。渤海湾盆地沙河街组和孔店组、鄂尔多斯盆地长7段、准噶尔盆地芦草沟组和风城组、松辽盆地青山口组均可按照本研究提出的分类方案划分页岩油类型。笔者希望本文可以帮助石油工作者进一步深化对陆相页岩油甜点的认识,更加准确地计算中国陆相页岩油资源量,实现油气资源分级开发利用。

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