



## 煤层群煤系多套含气系统特征及其合采效果 ——以铁法盆地阜新组为例

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# 煤层群煤系多套含气系统特征及其合采效果 ——以铁法盆地阜新组为例

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**摘要** 煤系含气系统特征影响了煤层气井多产层合采的工程效果。基于铁法盆地阜新组层序地层、含气单元及其分隔层特征,划分了叠置的多套含气系统,分析了发育煤层群煤系多套含气系统的含气性、渗流条件和流体压力特征,探讨了其对上、下含煤段分采及合采工程效果的影响。研究认为,白垩系阜新组上含煤段5个含气单元为一套统一的含气系统,下含煤段7个含气单元可划分为三套含气系统。湖进体系域下,三角洲前缘沉积环境形成的含气单元资源丰度较大,滨浅湖沉积环境形成的(泥质)粉砂岩厚度大且构成稳定的隔水阻气层,是研究区含气系统划分的关键层。随埋深的增加,各含气系统储层孔隙度、平均渗流孔径、裂隙发育情况、储层渗流能力降低趋势明显。上下含煤段分属明显不同的含气系统,其储层压力、解吸压力差异较大,煤层气合采时上下含煤段储层产出气液具不同步性,气水产出层间干扰大。阜新组煤层气合采效果由好到差的相对顺序是上含煤段合采、上下含煤段合采、下含煤段合采。阜新组上含煤段独立开发的效果最好,是由于各个含气单元形成了一套兼容性含气系统,储层具有明显地富气高渗优势。

**关键词** 铁法盆地;煤层群;煤层气;含气系统;合层开采

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## 0 引言

煤系地层煤层气、页岩气、致密砂岩气的含气系统及其叠层成藏特征是近年来叠置含气系统研究的热点<sup>[1]</sup>。多套含煤层气系统的研究主要集中于晚古生代石炭二叠纪的煤系地层<sup>[2-4]</sup>。我国具有工业开发价值的煤层气赋存在晚古生代的石炭二叠系、中生代的侏罗系、白垩系下统、新生代的古近系等多个煤系<sup>[5]</sup>。中生代及其以后形成的煤系地层,往往以厚含煤段的形式发育,以侏罗世、白垩世发育的煤层尤为典型,含煤段往往发育多个,单个含煤段厚度大,段内煤层层数多,称之为煤层群<sup>[6]</sup>;煤层群条件下,单煤

层厚度变化大,单层对比困难,但部分含煤段发育稳定,呈现出规律性的层序地层,含气单元被粉砂岩、泥页岩等封闭性较好的碎屑沉积岩隔开,垂向上形成了多套含煤层气系统。这种叠置的多套含煤层气系统,主要分布于东北、西北区<sup>[7]</sup>,如吐哈盆地<sup>[6]</sup>、铁法盆地<sup>[8]</sup>、阜新盆地<sup>[9]</sup>、准噶尔盆地南缘<sup>[10-11]</sup>等。以铁法盆地为例,其含煤地层为白垩系下统阜新组上下两个含煤段,上下含煤段内煤层数量均可达40层以上,上下含煤段被平均厚度100 m左右的中部砂、泥岩段隔开,是典型的煤层群煤系多套含煤层气系统发育区。单井分段压裂合层开采是此类煤层气藏的主要开发方式,合层开采层间矛盾影响了煤层气井合采

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效果,铁法盆地煤层群条件下的多套含气系统特征造成了不同含煤段产能差异显著<sup>[12]</sup>。查明各含气系统开发地质特征及其兼容性,是工程迫切需要解决的地质理论问题。非常规油气甜点段形成往往受控于区域性多种地质事件沉积耦合<sup>[13]</sup>。构造运动和气候变化导致沉积基准面和湖水面的周期性变化<sup>[14]</sup>,使得陆相断陷聚煤盆地在不同演化阶段形成了具有一定韵律的层序地层。但层序体系域的差异,影响了聚煤环境、特征、强度,也使得共生的岩石岩性差异性显著。这种差异一方面影响了煤储层含气性、渗流能力,另一方面,含煤地层中低孔渗条件的隔水阻气层的发育,分隔了煤层气含气单元<sup>[15]</sup>,垂向上形成了不同的含气系统,而层序地层特征影响或控制了含气系统划分、含气系统之间的沟通与联系<sup>[4,16]</sup>。基于层序地层格架<sup>[17-18]</sup>、含气单元及其分隔层的特征,来划分含气系统具有较好地地质理论依据。含气系统渗流条件<sup>[19]</sup>和流体压力特征差异<sup>[3,20]</sup>是合层开采间干扰来源的关键,本文试图从含气系统划分、各系统含气性、渗流条件和流体压力特征来探讨煤层群条件下的多套含气系统发育特征及其对煤层气井合采的影响。

## 1 地质背景与层序地层

铁法盆地位于松辽盆地南缘,是一断陷盆地,盆地内部整体显示为NNE向的向斜,呈现东缓西陡的不对称形态。区内煤层气开发区主要位于大兴井田富煤带,轮廓主要受向斜控制,向斜内又被不同方向正断层所切割,断层不导水、不导气(图1)。区内地层由老至新为太古界前震旦系、中生界的白垩系下统、新生界第四系。白垩系下统阜新组为本区主要含煤建造。本区阜新组自下而上发育四个沉积序列,每个沉积序列对应一个沉积组合分段,四个沉积序列依次为:底部砂砾岩段,由扇泥石流沉积和砾质河道沉积组成,垂向上总体向上变细,下部主要为粗碎屑沉积物,上部逐渐过渡为以砂岩为主,夹泥岩;下含煤段,三角洲沉积环境下,水下分流河道主要形成砂砾岩段,分流间湾或泥炭沼泽主要形成砂岩与煤层的交互层段,沉积微相的交替变换,在垂向上形成了四个沉积旋回,该段含煤60层左右,地层厚度平均250 m;中部砂泥岩段,湖泊沉积环境下,浅湖泥或滨湖砂坝形成了厚度大,胶结致密,厚度相对稳定的(泥质)粉砂岩段,厚度平均60 m;上含煤段,分流间

湾或泥炭沼泽与水下分流河道的交互发育,形成了煤层与砂岩的互层结构,该段含煤50层左右,厚度平均150 m。为明确区内垂向沉积序列上的共性,以区内DT31井为例,划分了阜新组的层序。层序Ⅰ,底界为盆地基底与底部砂砾岩的界面,顶界面为下含煤段中部的砂砾岩底部;层序Ⅱ,底界面为下含煤段中部的砂砾岩底部,顶界面为上含煤段中部粗砂岩底部;层序Ⅲ,底界面为上含煤段中部粗砂岩底部,顶界面为上含煤段之上的砂砾岩底部,界面之上主要为粗砂、砂砾岩,为辫状河滞留沉积,该界面之下煤层伪顶、直接顶被辫状河大范围侵蚀,有时冲蚀煤层形成冲刷带<sup>[21]</sup>。层序具三元结构,由低水位体系域(LST)、水进体系域(TST)、高水位体系域(HST)构成(图2)。

本区地层主要形成于陆相三角洲—湖泊沉积体系;区内煤层主要形成于湖进或高水位体系域的三角洲沉积环境,沉积亚相相对稳定,煤层段厚度大,但沉积微相转换相对频繁,因此煤层多以厚度小、层数多的煤层群发育,且煤层群发育段被湖泊沉积环境下形成的致密碎屑沉积岩所分隔。三角洲前缘亚相下,含煤段内的煤、泥岩、粉砂岩主要形成于分流间湾及泥炭沼泽,粗粒砂岩主要形成于水下分流河道,上下含煤段垂向上各显示4个左右的沉积旋回(图2)。中部砂岩段,主要是滨浅湖沉积环境下形成的粉砂岩和泥质粉砂岩,其低孔渗的特征及100 m左右的稳定厚度,使其成为封闭性极好的阻水隔气层。

## 2 含气单元特征及含气系统划分

### 2.1 煤层分布特征

区内煤层呈煤层群发育,具有单层煤厚度小,煤层层数多,煤层累计厚度大的特征。上含煤段,厚90.4 m,发育有48层煤,单层煤厚0.2~1.3 m,大部分煤层煤厚0.2~1.0 m,累计煤厚24.1 m。下含煤段,厚130.3 m,发育有64层煤,单层煤厚0.1~1.3 m,大部分煤层煤厚0.2~0.8 m,累计煤厚31.8 m。

### 2.2 含气单元分布特征

研究区主要的含气储层为煤层,将煤层相对集中的煤层群划分为一个含气单元。按本区煤层群发育特征,以煤层之间间隔小于2.7 m为上限,可将阜新组上含煤段划分为5个含气单元,下含煤段分为7个含气单元(表1)。煤厚小于1 m的单煤层含气单元资源量有限,开发价值相对较低,在含气单元划分

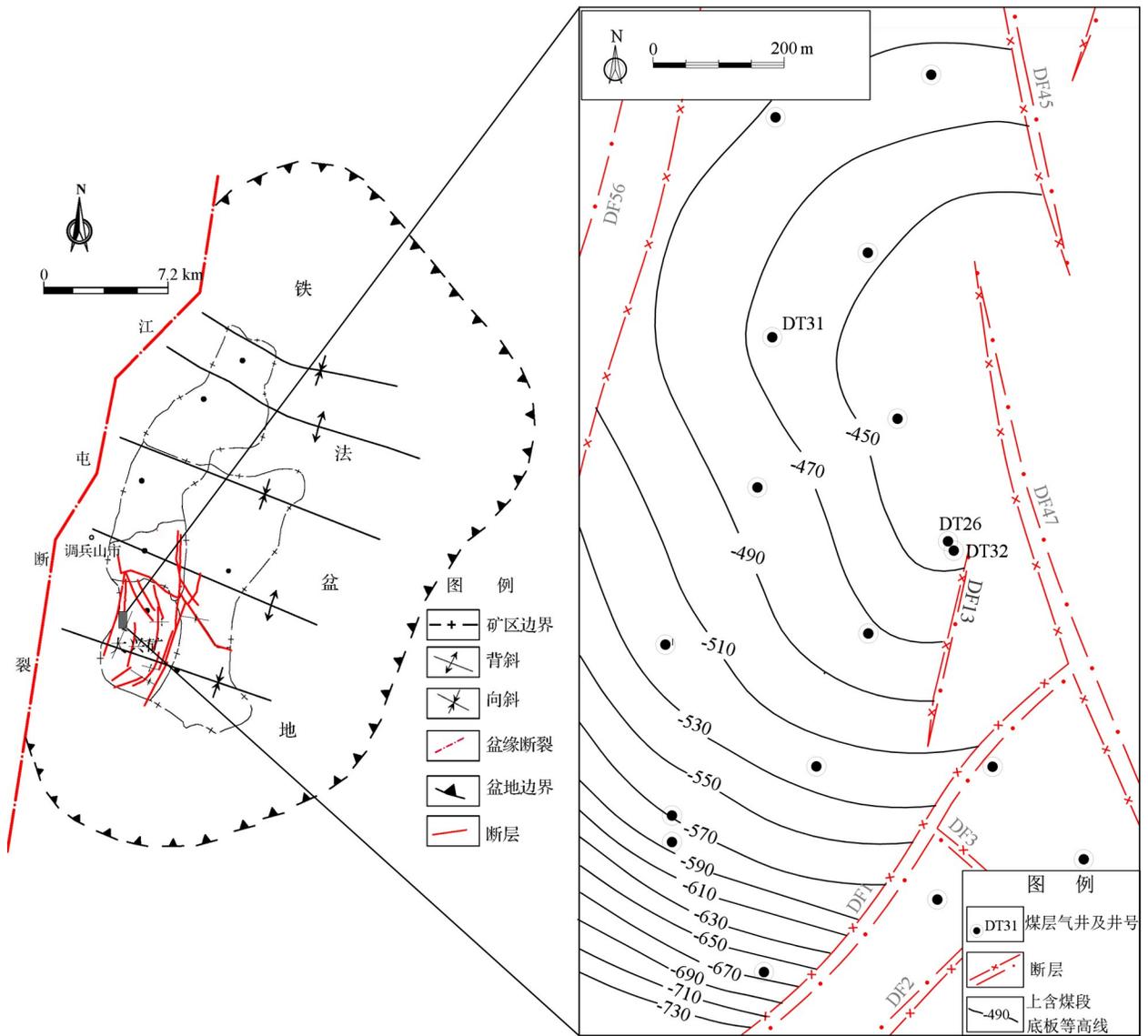


图1 铁法盆地及研究井区构造简图  
 Fig.1 Structure of Tiefa Basin and study area

时,去除了煤厚小于1 m且距离邻近含气单元超过8 m的单煤层含气单元。阜新组上含煤段共5个含气单元,含气单元厚度为2.7~18.1 m,各含气单元煤层累厚1.9~8.0 m,含煤系数31.3%~69.6%,含气单元彼此间隔3.3~5.7 m。阜新组下含煤段共7个含气单元,含气单元厚度为2.5~18.4 m,各含气单元煤层累厚1.9~10.7 m,含煤系数24.9%~75.5%,含气单元彼此间隔4.4~10.0 m。

就阜新组上下含煤段对比来看,上含煤段含气单元累厚70.3 m,煤层累厚22.4 m,含煤系数31.9%;下含煤段含气单元累厚114.0 m,煤层累厚30.7 m,含煤系数26.9%。造成下含煤段含煤系数较低的主要

原因是下含煤段各含气单元间隔相对较大,下含煤段D-IV距离上下邻近含气单元距离为12.8 m、8.7 m, D-VII距邻近含气单元距离为10.0 m。

U- I 含气单元内中部储层的含气量最高,靠近含气单元顶底界面,储层含气量则逐渐降低(图3);垂向上煤层集中发育区中部的含气量相对较高,该规律也见于黔西<sup>[20]</sup>、山西古交区块<sup>[22]</sup>。在三角洲前缘的分流间湾和泥炭沼泽沉积环境下,U- I 含气单元内主要发育粉砂岩、泥质粉砂岩、泥岩和厚度较大的煤层,利于煤层气储集,煤层气不易扩散运移,因此含气单元中部含气量相对较高;靠近含气单元顶底界面,则主要发育中砂—粗砂岩,利于煤层气的扩散

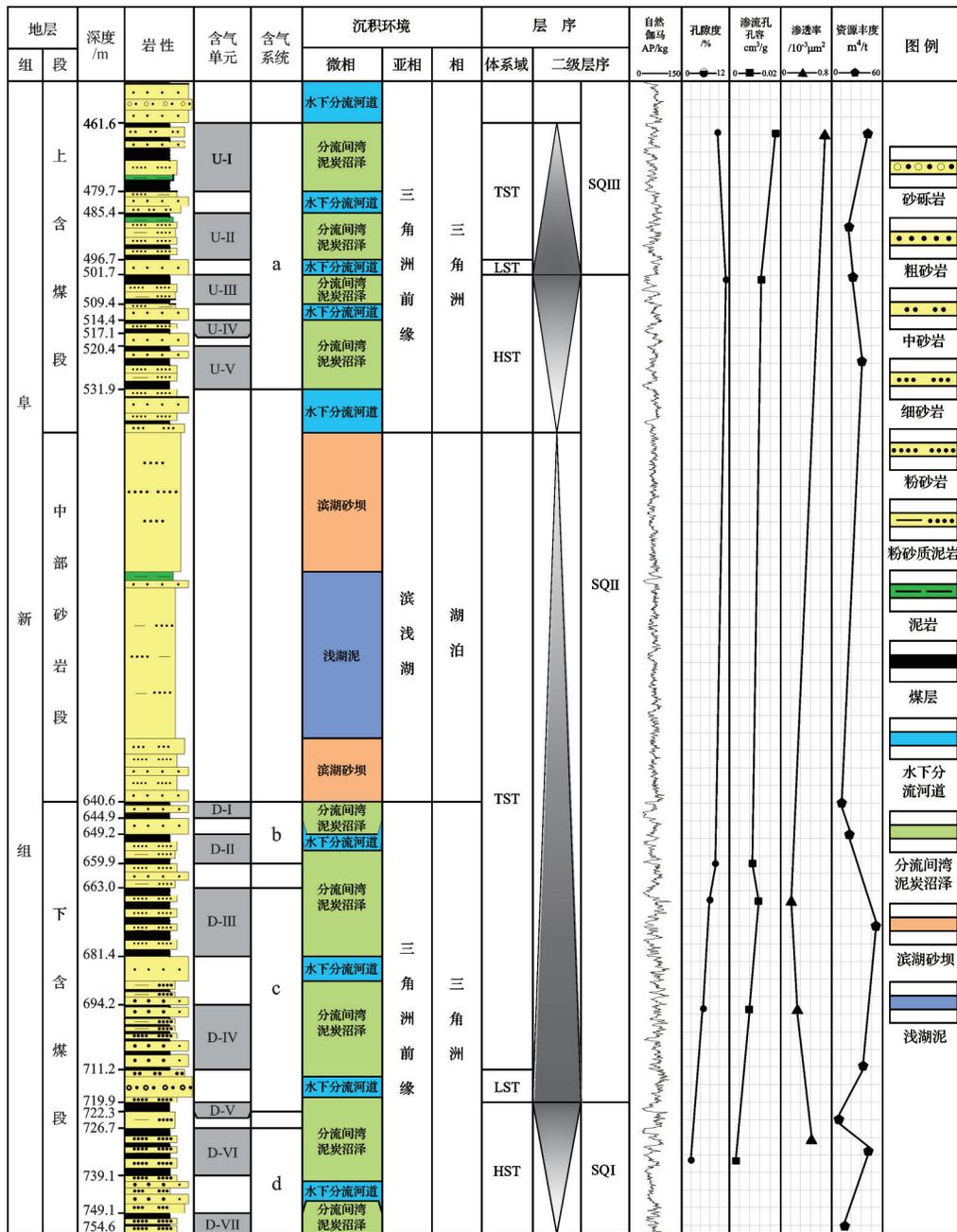


图2 DT31井阜新组含煤段岩性岩相、层序及含气系统发育特征

Fig.2 Lithology, lithofacies, stratigraphic sequence and gas-bearing system of coal-bearing section of the Fuxin Formation at well DT31

运移,因此含气单元顶底界储层含气量相对较低。以各含气单元的平均含气量与煤厚的乘积作为含气单元资源丰度衡量指标。各含气单元的资源丰度与含气量相关性较差(图4)。三角洲前缘的分流间湾和泥炭沼泽沉积环境形成的煤层群含气单元,含气量变化较大,但煤厚变化更大,因此评价各含气单元资源潜力,资源丰度更具代表性。总体来看,相对于低水位体系域和高水位体系域,湖进体系域下,三角

洲前缘的分流间湾和泥炭沼泽沉积环境形成的含气单元资源丰度较大,如U- I 和D- III。

### 2.3 隔水阻气层段及含气系统划分

陆相沉积环境下,致密的碎屑沉积岩如泥岩、粉砂岩封闭性好,可将其视为隔水阻气层<sup>[6,15,23]</sup>,将煤、细砂岩、中砂岩、砾岩视为透水(含气/水)层,即开放层。同一套含气系统内部应发育统一的流体压力系统<sup>[1-24]</sup>,各含气单元之间可实现流体的沟通,统一含气

表1 DT31井含气单元特征  
Table 1 Properties of gas-containing units at well DT31

煤段	含气单元	埋深/m		含气单元厚度/m	含气单元煤层累厚/m	煤层数/层	含煤系数/%	煤厚		单元内岩层总数/层	煤层间隔最大/m
		顶板	底板					最大/m	最小/m		
上	U-I	461.6	479.7	18.1	8.0	14	44.2	0.9	0.2	13	2.7
	U-II	485.4	496.7	11.3	3.6	9	31.3	0.7	0.2	8	2.3
	U-III	501.7	509.4	7.7	4.8	8	61.5	1.3	0.3	7	1.3
	U-IV	514.4	517.1	2.7	1.9	4	69.6	0.6	0.3	3	0.4
	U-V	520.4	531.9	11.4	4.2	11	37.1	0.9	0.2	10	2.1
下	D-I	640.6	644.9	4.3	2.3	3	52.3	0.9	0.6	2	1.7
	D-II	649.2	656.9	7.7	3.3	7	42.2	0.8	0.3	6	1.2
	D-III	663.0	681.4	18.4	10.7	20	58.4	1.2	0.1	19	1.0
	D-IV	694.2	711.2	17.1	4.3	11	24.9	0.6	0.3	10	2.1
	D-V	719.9	722.3	2.5	1.9	3	75.5	1.2	0.2	2	0.4
	D-VI	726.7	739.1	12.5	6.2	13	49.8	1.3	0.3	12	1.8
	D-VII	749.1	754.6	5.4	2.2	5	39.45	0.5	0.35	4	1.75

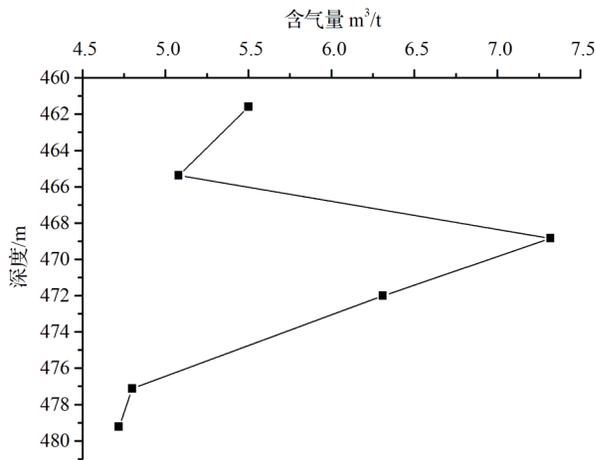


图3 U-I含气单元含气量随埋深变化  
Fig.3 Changes in gas content with buried depth in gas-containing Unit U-I

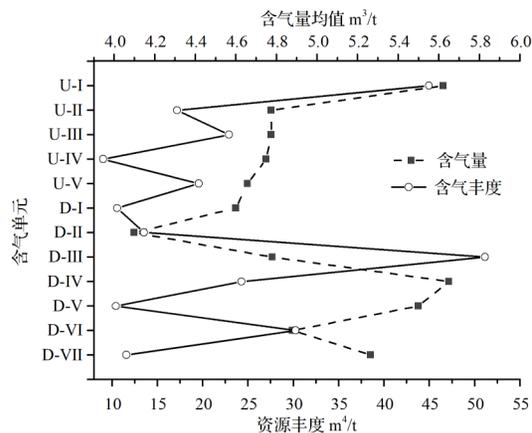


图4 各含气单元含气量均值及资源丰度对比  
Fig.4 Comparison of average gas content and resource abundance in each gas-containing unit

系统受控于煤层之间分隔层中开放层所占的比例。被隔水阻气层分隔的一个或多个含气单元即可划分为一套含气系统。层序地层格架在一定程度上决定了煤层群条件下的分隔层及开放层的分布<sup>[4]</sup>,也影响了含气系统的划分。

本区上含煤段底部含气单元U-V与下含煤段顶部含气单元D-I之间间隔是中部砂岩段,湖进体系域下滨浅湖沉积环境形成的粉砂岩及泥质粉砂岩,厚度大,达108.7 m,83%主要为隔水阻气层,封闭性强,上下含煤段流体难以沟通,使得上下含煤段不属于同一套含气系统(表2)。因此湖进体系域下,滨浅湖的浅湖泥或滨湖砂坝形成了厚度大且稳定的隔水阻气层,是研究区含气系统划分的关键层。

表2 阜新组上下含煤段分隔层特征

Table 2 Characteristics of separation layers in the upper and lower coal-bearing sections, Fuxin Formation

煤段	分隔层序号	分隔含气单元	分隔层总厚度/m	厚度/m	
				隔水阻气层	开放层
上	1	U-I & U-II	5.7	1.9	3.8
	2	U-II & U-III	4.9	0.42	4.5
	3	U-III & U-IV	5.0	1.3	3.7
	4	U-IV & U-V	3.3	0.63	2.7
-	-	U-V & D-I	108.7	90.4	18.3
下	1	D-I & D-II	4.3	0.6	3.7
	2	D-II & D-III	6.1	3.9	2.2
	3	D-III & D-IV	12.8	2.8	10
	4	D-IV & D-V	8.7	0.8	7.9
	5	D-V & D-VI	4.4	4.4	
	6	D-VI & D-VII	10.0	0.9	9.1

上含煤段5个含气单元之间,分隔层厚度较小,约3.3~5.7 m,开放层厚度占分隔层总厚度的66%~92%。在储层压裂后,各个含气单元之间沟通的可能性高,上含煤段5个含气单元可视为一套含气系统,成为含气系统a(表2)。下含煤段7个含气单元之间,D-II与D-III分隔层厚度6.1 m,且分隔层中73%为阻水阻气层,D-V与D-VI之间分隔层厚度4.4 m,均为隔水阻气层。据此,可将下含煤段分为三套含气系统,含气系统b,包含D-I与D-II含气单元;含气系统c,包括三个含气单元,D-III、D-IV、D-V;含气系统d,包括二个含气单元D-VI与D-VII(表2)。四套含气系统中,含气系统a资源潜力最大,其次,按从大到小分别为含气系统c、d、b(表3)。

### 3 含气单元孔渗特征

#### 3.1 含气单元渗流孔隙发育特征

利用高压汞注入法获得了煤的孔隙特征。将孔隙分为大孔(>1 000 nm)、中孔(100~1 000 nm)、过渡孔(10~100 nm)、微孔(<10 nm),视中孔及大孔为渗流孔隙。

含气系统a中U-I、U-III总孔容约( $7.37 \times 10^{-2} \sim 9.88 \times 10^{-2}$ )  $\text{cm}^3/\text{g}$ ;含气系统c中D-III、D-V总孔容约( $6.28 \times 10^{-2} \sim 7.95 \times 10^{-2}$ )  $\text{cm}^3/\text{g}$ ;含气系统d中D-VII总孔容 $5.62 \times 10^{-2} \text{ cm}^3/\text{g}$ 。随埋深增大,总孔容有逐渐降低的趋势,总体而言,含气系统a的平均总孔容较大(图5)。

随埋深增大,孔隙度也有逐渐降低的趋势,含气

系统a的储层平均孔隙度较大。含气系统a中U-I、U-III孔隙度约8.25%~11.60%;含气系统c中D-III、D-V孔隙度约7.56%~8.98%;含气系统d中D-VII孔隙度6.3%(图5)。

含气系统a中U-I、U-III渗流孔占总孔容的百分比约11.13%~27.4%;渗流孔孔容约 $0.90 \times 10^{-2} \sim 2.37 \times 10^{-2} \text{ cm}^3/\text{g}$ ;含气系统c中D-III、D-V渗流孔占比9.24%~9.56%,渗流孔孔容约 $0.58 \times 10^{-2} \sim 0.76 \times 10^{-2} \text{ cm}^3/\text{g}$ ;含气系统d中D-VII渗流孔占比8.11%,渗流孔孔容 $0.46 \times 10^{-2} \text{ cm}^3/\text{g}$ 。含气系统a的渗流孔容明显高于含气系统c和d的,随埋深增大,渗流孔孔容明显降低(图6)。

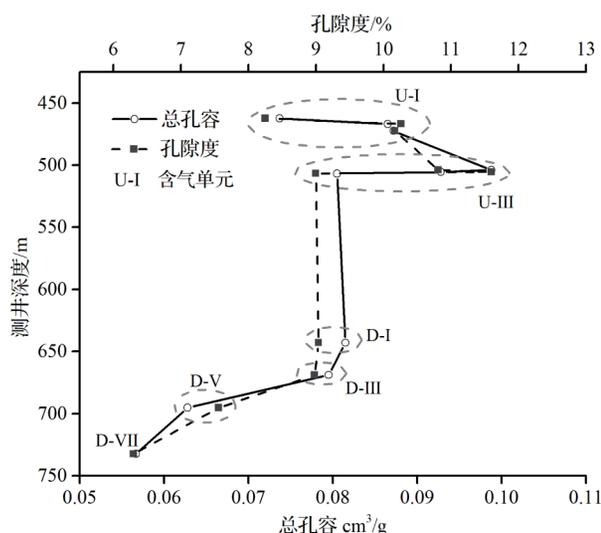


图5 各含气单元孔隙度及总孔容特征  
Fig.5 Porosity and total pore volume of each gas-containing unit

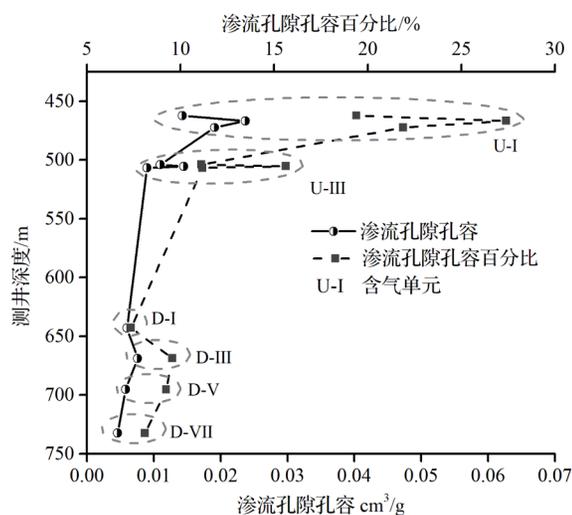


图6 各含气单元渗流孔孔容特征  
Fig.6 Percolation pore volume of each gas-containing unit

表3 各含气系统及其资源潜力  
Table 3 Resource potential of each gas-bearing system

含气系统	含气单元	含气量均值/ $\text{m}^3/\text{t}$	煤厚/m	资源丰度/ $\text{m}^3/\text{t}$
a	U-I	5.6	8.0	45.0
	U-II	4.8	3.6	17.2
	U-III	4.8	4.8	22.9
	U-IV	4.8	1.9	9.0
	U-V	4.7	4.2	19.6
b	D-I	4.6	2.3	10.6
	D-II	4.1	3.3	13.5
c	D-III	4.8	10.7	51.1
	D-IV	5.7	4.3	24.3
	D-V	5.5	1.9	10.5
d	D-VI	4.9	6.2	30.3
	D-VII	5.3	2.2	11.6

### 3.2 含气单元裂隙及储层渗流特征

采用国产HK-4型渗透率自动测定仪,固定围压和孔隙压力测试储层的N<sub>2</sub>渗透率,获得了DT31井U-I、D-III、D-IV、D-V四个含气单元的储层渗透率。含气系统a中U-I渗透率为(0.20~1.28)×10<sup>-3</sup> μm<sup>2</sup>,含气系统c中D-III、D-IV、D-V渗透率为(0.07~0.12)×10<sup>-3</sup> μm<sup>2</sup>,总体而言,含气系统a储层渗流能力明显好于含气系统c,随着储层深度的增加,储层渗透率降低。含气单元U-I内,越靠近含气单元中部,储层渗流能力越高(图7)。

DT31井含煤段全层段进行煤岩心取样,按每10 cm中发育裂隙条数观测统计了割理发育密度。含气系统a中U-I、U-III、U-IV的面割理发育密度约0.83~1.67条/cm,平均裂隙密度为1.22条/cm,裂隙充填度为10%左右;含气系统c中D-III、D-IV、D-V面割理密度约0.54~1.40条/cm,平均裂隙密度为0.96条/cm,裂隙充填度为30%左右;含气系统d中D-VI面割理密度1条/cm,裂隙充填度达40%左右。随着埋深增大,裂隙充填程度加大,裂隙充填物主要为白色薄片状或脉状方解石。含气系统a的裂隙发育条件总体要优于含气系统c及d,与储层渗透率变化规律基本相符(图8)。

### 3.3 含气系统压力特征分析

储层压力和临界解吸压力是鉴别统一含气系统的关键参数,统一含气系统应具有相近的压力梯度<sup>[25]</sup>。DT31井作为上下含煤段分段压裂合层排采井,下含煤段三套含气系统之间分隔层厚度为4.4~6.1 m,储层压裂改造形成的垂向压裂裂缝具备穿透

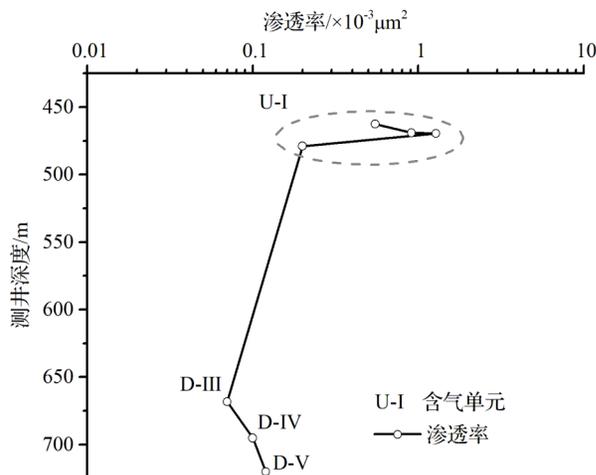


图7 各含气单元渗透率

Fig.7 Permeability of each gas-containing unit

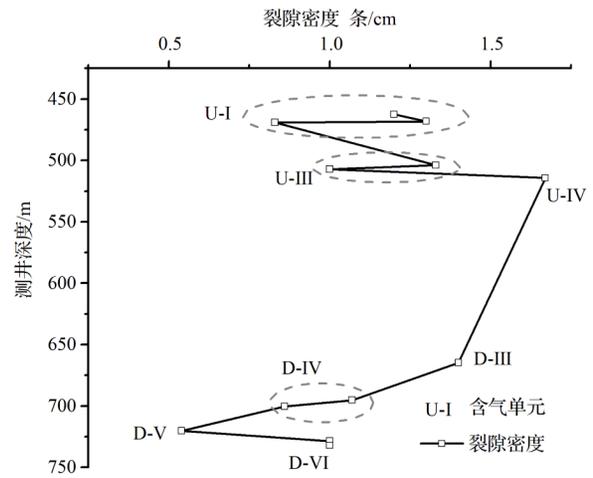


图8 各含气单元裂隙密度

Fig.8 Face cleat density of each gas-containing unit

分隔层能力,储层改造具有连通三套含气系统可能性。抽水工程试验结果表明其上含煤段(对应含气系统a)储层对应井内静水液面深度为83 m(储层埋深480 m),储层压力为4.1 MPa,储层压力梯度为1.02 MPa/hm;下含煤段(对应含气系统b、c、d)储层对应井内静水液面深度为148 m(储层埋深755 m),储层压力为6.2 MPa,储层压力梯度为0.83 MPa/hm。排采过程中,DT31井具有两个明显的解吸液面深度,第一个为液面深度223 m(储层埋深462 m),临界压力为2.4 MPa,临界解吸压力梯度为0.52 MPa/hm;第二个为液面深度379 m(储层埋深502 m),临界解吸压力为1.3 MPa,临界解吸压力梯度为0.25 MPa/hm。上下含煤段压力梯度差异较大,证实DT31井上下含煤段不属于统一的流体压力系统。

储层压力对应液面深度的差异,反映了储层产水时间和供水能力的巨大差异。根据煤层气井产水特征,排采时井内液面降至储层压力对应液面深度时,相应储层开始产水;上下含煤段储层压力的差异,会使上含煤段含气系统对下含煤段的产水具有一定的抑制性,排采初期埋深较大的下含煤段会滞后产水。在储层压力对应液面深度及临界解吸压力对应液面深度之间,产层供水能力逐渐增大,在临界解吸期间,产层供水能力变幅较大,在临界解吸期之后,产层供水能力呈起伏式下降,产层供气能力逐渐增强<sup>[8]</sup>。上下含煤段对应储层压力及临界解吸压力液面深度的不一致反映了上下含煤段内煤层气产层供水供气的不同步,这种不同步会造成极大的层间干扰,进而影响产能<sup>[8, 12]</sup>。

#### 4 多套含气系统合采工程效果

区内DT31、DT26、DT32井位邻近,DT26和DT32建设于同一井场,DT26井产层为上含煤段(对应含气系统a),DT32井产层为下含煤段(对应含气系统b、c、d)。DT31井为上、下含煤段合采井。DT31井产气1 787天,累计产气 $4.08 \times 10^6 \text{ m}^3$ ,平均日产气 $2\ 280 \text{ m}^3/\text{d}$ ,平均日产水 $5.6 \text{ m}^3/\text{d}$ ;DT26井产气2 789天,累计产气 $9.09 \times 10^6 \text{ m}^3$ ,平均日产气 $3\ 247 \text{ m}^3/\text{d}$ ,平均日产水 $2.9 \text{ m}^3/\text{d}$ ;DT32井产气2 846天累计产气 $3.84 \times 10^6 \text{ m}^3$ ,平均日产气 $1\ 349 \text{ m}^3/\text{d}$ ,平均日产水 $2.7 \text{ m}^3/\text{d}$ (图9)。上含煤段的产层贡献率高于下含煤段,上、下含煤段产层贡献率比值是2.4:1。

上下含煤段合采井DT31井平均日产量仅有上含煤段单采井DT26井的70%,单井累计产气量仅有上含煤段单采井的45%,煤层气井生产效果说明合采存在较大的层间干扰。多套含气系统合采具有地质条件及阈值限制,条件或参数主要包括储层压力梯度、储层临界解吸压力梯度、含气系统分隔层厚度、合采含气系统顶底板深度差异、合采产层渗透率等<sup>[3,20]</sup>。滇东地区合采井合采层储层压力梯度差异系数控制在8%以内<sup>[20]</sup>,DT31井合采层储层压力梯度系数为18%~22%;DT31井合采层顶底板深度差异达293 m,该值大于绝大部分地区合采产层的顶底板深

度间隔<sup>[3,20,26-27]</sup>;厚达108 m的中部砂岩段对上下含煤段形成有效分隔,形成了特征差异较大的含气系统;多套含气系统产水产气的不同步,产生了较大的层间干扰作用;多种因素的综合作用导致上下含煤段合采井生产效果欠佳。

上含煤段各个含气单元之间主要由开放层分隔,使得上含煤段形成了一套流体压力相对统一的含气系统;同时上含煤段煤层气资源丰度达 $113.7 \text{ m}^4/\text{t}$ ,已高出沁水盆地南部的高产井产层资源丰度( $99 \text{ m}^4/\text{t}$ )15%<sup>[8]</sup>,同时储层孔隙度8.25%~11.60%,渗流孔容大,裂隙发育且填充度低;储层富气高渗特征使得上含煤段单采井煤层气开发效果较好。

下含煤段含气单元多于上含煤段,部分分隔层属于隔水阻气层,将下含煤段分割为三套叠置的含气系统,但储层压裂改造具备连通三套含气系统可能性,DT31井三套含气系统内各含气单元之间最大分隔层厚度未超过12.8 m,推测下含煤段内各含气系统彼此干扰程度有限;储层孔裂隙分析及渗流测试结果表明,埋深的增加,下含煤段各个含气系统的储层渗流孔容、裂隙发育情况、储层渗透率降低趋势明显;DT32井平均日产水仅 $2.7 \text{ m}^3/\text{d}$ ,也证实了储层渗流能力低于上含煤段储层;因此下含煤段煤层气开发效果要弱于上含煤段。

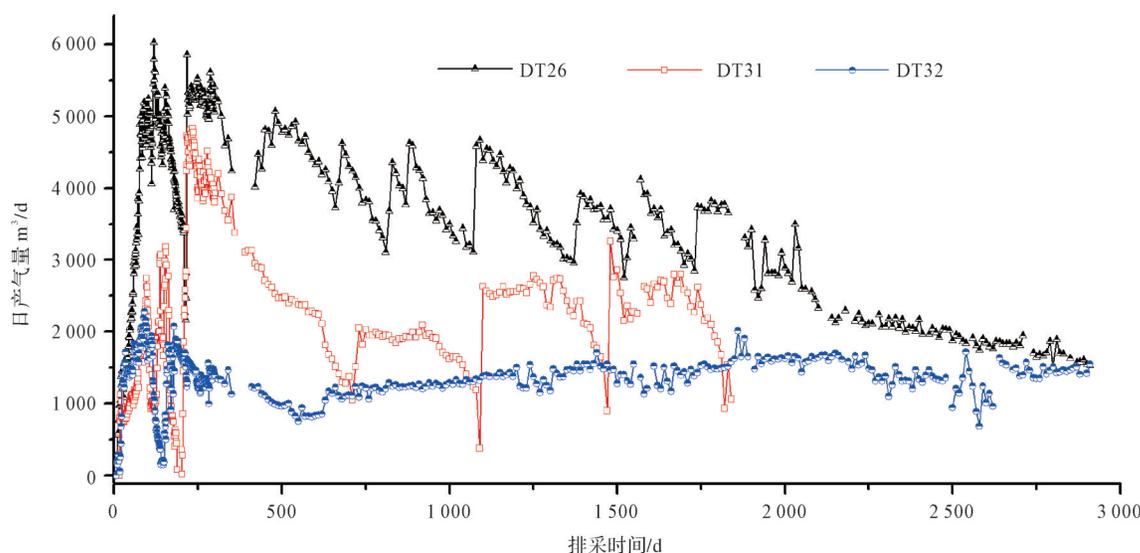


图9 阜新组上下含煤段分采及合采井产气特征

DT26产层为上含煤段,DT32产层为下含煤段,DT31产层为上、下含煤段

Fig.9 Gas production characteristics of Fuxin Formation in Tiefu Basin

Upper coal-bearing section is the principal gas-producing formation in Well DT26. Lower coal-bearing section is the principal gas-producing formation in well DT32. Both upper and lower coal-bearing sections are the gas-producing formations in well DT31

## 5 结论

(1) 铁法盆地白垩系阜新组上含煤段5个含气单元形成了一套统一的含气系统,下含煤段7个含气单元可划分为三套含气系统。煤层群煤系在湖进体系域下,三角洲前缘的分流间湾和泥炭沼泽沉积环境形成的含气单元资源丰度较大;湖进体系域下,滨浅湖的浅湖泥或滨湖砂坝形成了厚度大且稳定的隔水阻气层,是研究区含气系统划分的关键层。

(2) 随埋深的增加,储层孔隙度、平均渗流孔容、裂隙发育情况、储层渗透率降低趋势明显;上下含煤段储层压力梯度、解吸压力梯度差异大,煤层气合采时上下含煤段储层产出气液具有不同步性;上下含煤段含气系统储层流体压力和储层渗流能力的差异,制约了上下含煤段含气系统的合层开采。

(3) 阜新组煤层气合采效果由好到差是上含煤段合采、上下含煤段合采、下含煤段合采,上下含煤段多套含气系统合采效果不佳。阜新组上含煤段独立开发的效果最好,是由于其各个含气单元彼此形成了一套兼容性较好含气系统,同时其资源丰度最高,渗流孔容、裂隙密度较大,储层的渗流能力最好。

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## Characteristics of Multi-gas-bearing Systems within Coal Seam Groups and the Effect of Commingled Production: A case study on Fuxin Formation, Cretaceous, Tiefa Basin

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**Abstract:** The characteristics of multi-gas-bearing systems affect the outcome of commingling the production of coalbed methane (CBM) from multiple strata. In this case study, multiple superimposed gas-bearing systems in the Fuxin Formation, Tiefa Basin, are categorized by their stratigraphical sequence and the properties of the non-gas-bearing strata lying between the gas-containing units. The gas-bearing characteristics, seepage conditions and fluid pressures of each CBM system were analyzed to consider the effect of separate and commingled production of gas from the upper and lower coal sections. It was found that each of the five gas-containing units in the upper coal-bearing section are all part of a single gas-bearing system, whereas the seven gas-containing units in the lower coal-bearing section comprised three distinct gas-bearing systems. A transgressive lacustrine system tract had resulted in a relatively large abundance of CBM gas-bearing units at the delta front. In the study area, thick, stable water- and gas-barrier layers of lake-shore and shallow-lake subfacies form the strata between the gas-bearing systems. With greater burial depth, the reservoir porosity, average seepage pore volume, fracture development and reservoir seepage capacity of each gas-bearing layer all decrease significantly. The large difference in reservoir pressure and critical desorption pressure between the upper and lower coal-bearing sections occur because they belong to different gas-bearing systems. The supply of both water and gas in the upper and lower sections are not synchronized in commingled production of the upper and lower coal sections, causing very significant interference in gas and water production. Commingled production of CBM, from best to general, is: (i) from the upper coal-bearing section; (ii) from the upper-plus-lower coal-bearing sections; and (iii) production from the lower coal-bearing section only. Production (i) is best because its various gas-containing units form a single compatible gas-bearing system, and its reservoirs also have the obvious advantages of rich gas content and high permeability.

**Key words:** Tiefa Basin; coal seam groups; coalbed methane; gas-bearing system; commingled production