

# 沉积环境对鹤岗煤田煤岩储集空间的影响

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**摘要:**为探明沉积环境对煤岩储集空间的控制作用,应用扫描电镜、低温氮吸附和聚类分析等多种分析测试手段,对鹤岗煤田城子河组煤岩孔隙、裂隙和成煤环境进行系统研究。结果表明:鹤岗煤田孔隙结构存在4种孔隙模型,从模型I到模型IV,孔隙形态和裂隙类型逐渐多样化。孔隙的吸附能力增强,但解吸难度加大;煤相分析显示鹤岗煤田主要聚煤期由南向北富水程度加深,埋藏速度增大。扇三角洲为主要聚煤环境,北部煤层厚度和稳定性优于南部;沉积环境对煤层孔隙结构和裂隙发育具有一定的控制作用。由北向南,灰分含量增加,孔隙系统逐渐复杂,裂隙数量和类型逐渐多元化。研究认为鹤岗煤田储集空间具有南繁北简的特征,渗流能力存在南强北弱的特点。

**关键词:**鹤岗煤田;孔隙模型;储集空间;煤相;沉积环境

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## Influences of depositional environment on reservoir space of coal in Hegang Coalfield

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**Abstract:** In order to discover the effect of depositional environment on reservoir space of coal, pore and fracture characteristics and formation environment of coal in Chengzihe Formation of Hegang Coalfield were systematically analyzed using a series of analytical methods including scanning electron microscope, low temperature nitrogen adsorption and cluster analysis. The results showed that there were four types of pore models in Hegang Coalfield. From Model I to Model IV, the pore morphology and types of fissure gradually became diversified. Meanwhile, with the increase of pore adsorption capacity, desorption became more difficult. Coal facies analysis revealed that from south to north the overlying water deepened and the speed of burial accelerated during main coal-forming period of Hegang Coalfield. Fan-delta was the main coal accumulating environment and the thickness and stability of coal seam in the north were superior to the south. The depositional environment had a certain influence on pore structure and fracture development. From north to south, increasing ash content and more complicated pore system were observed and the number and types of fracture gradually diversified. It is concluded that the reservoir space of the south is more complex than the north and the porosity and permeability of the south are larger than the north.

**Key words:** Hegang Coalfield; pore model; reservoir space; coal facies; depositional environment

## 0 引言

油气勘探未来将进入海域深水、陆地深层、非常规油气三足鼎立的时代<sup>[1]</sup>,而且非常规油气资源在能源格局中的战略地位日益凸显<sup>[2]</sup>。近年来,伴随勘探理论认识的深化和开发技术的进步,非常规勘探得以快速发展,并将研究和评价的核心问题聚焦

在寻找有利储层<sup>[3-4]</sup>。前人对煤系沉积特征开展了大量的研究,认为河流三角洲平原,曲流河体系泛滥平原,冲积扇前缘平原及湖滨利于煤层发育,解决了寻找陆相有利聚煤环境的问题<sup>[5]</sup>。煤相研究进一步解决了煤层特征问题,可以得出有关成煤原始物质、成煤沼泽环境及其控制因素等反映煤层成因方面的信息<sup>[6-7]</sup>。煤层气是非常规勘探的重点领域,

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研究其孔隙结构及裂隙特征对煤层气吸附能力和渗流行为的控制作用,至今方兴未艾<sup>[8-12]</sup>。煤岩的多孔性使得煤储层具有储气和允许煤层气解吸、扩散和渗流的能力,因此,研究煤储层中储集空间及其控制因素对煤层气的勘探开发和可采性评价都具有非常重要的意义<sup>[13-14]</sup>。鹤岗盆地经过多口井的钻探证实该地区存在较大的煤层气勘探潜力<sup>[15]</sup>。与此同时,鹤岗盆地构造背景复杂、后期改造强烈,煤储层物性非均质性强且孔渗性与含气饱和度偏低,使煤层气勘探工作极具挑战性。前人的研究或关注宏观成藏条件,或着重微观孔隙特征,忽略了两者的内在联系。因此,笔者以鹤岗煤田孔隙模型为切入点,分析不同孔隙模型的微观特征,探讨成煤环境对煤储层孔隙和裂隙的控制作用,为确定煤层气富集区和优选有利目标提供理论依据。

## 1 样品及试验方法

为客观和全面地反映鹤岗煤田孔隙系统的特征,19块样品取自鹤岗煤田益新矿、鸟山矿、南山矿、兴安矿、峻德矿城子河组(图1)。

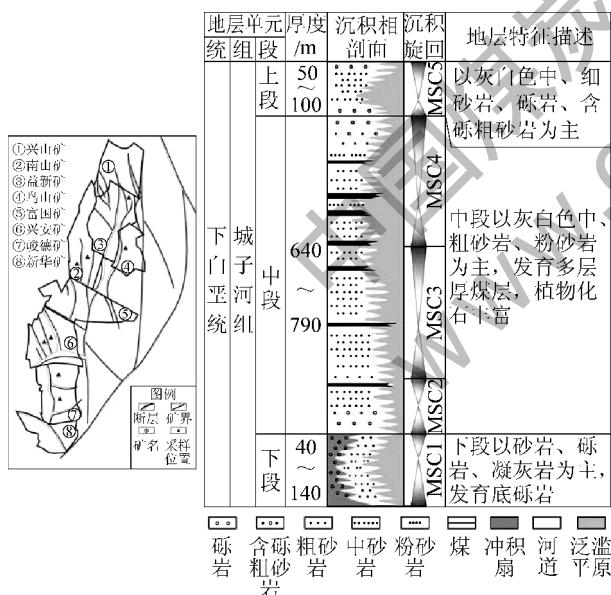


图1 鹤岗煤田构造纲要图、取样位置及地层综合柱状

Fig. 1 Structure sketch map samples location comprehensive stratigraphic profile in Hegang Coalfield

对同一沉积期(MSC4)煤岩分别进行扫描电镜观察、能谱分析和低温氮吸附试验。其中对煤岩表面孔隙观察采用S-4800场发射扫描电镜完成。低温氮吸附试验由ASAP2020比表面积仪完成,首先样品在100℃真空脱气3 h,然后在350℃去除有机

物,最后在华氏温度77°的液氮环境中进行低温氮吸附试验,孔径测量范围0.35~500.00 nm。在相对压力0.001~0.998范围内,利用BET模型进行比表面积分析,利用BJH模型进行体积和平均孔径的计算。

## 2 结果讨论

根据获取的孔隙结构数据可知,样品比表面积0.192~4.105 m<sup>2</sup>/g,平均1.926 m<sup>2</sup>/g(表1)。微孔所占比例为47.7%~94.5%,平均73.57%;小孔所占比例为3.50%~29.29%,平均17.69%;大孔平均含量低于10%。上述数据表明鹤岗煤田孔隙结构参数变化区间较大,必然导致孔隙结构特征的差异,需要从样品之间的相似性着手,进一步探讨这种差异性带来的影响。

### 2.1 聚类分析

聚类分析是统计学中研究“物以类聚”问题的多元统计分析方法,它能根据数据的特征,按照亲疏程度在没有先验知识的情况下进行自动分类,类内部个体具有相似特征<sup>[16]</sup>。聚类分析针对样本和变量又分为Q型和R型,所研究对象是单个煤岩样品之间的差异性,因此采用Q型聚类分析方法。在分析个体之间亲疏程度时,需要首先定义个体与小类之间的距离,采用离差平方和法,该方法根据个体特征逐渐聚类,通常作为样品聚类的首选方法。

样品数据主要包括煤岩工业分析、组分、孔隙结构和吸附能力等参数。灰分、镜质组含量等,反映煤岩质量;比表面积、兰氏体积等可以评价煤岩的吸附能力;总孔体积、平均孔直径和孔隙含量主要定性判别煤岩渗流能力。通过聚类分析可以发现,煤岩样品大体可以分为峻德矿、兴安矿、南山矿和益新-鸟山矿4类(图2)。

### 2.2 孔隙模型及储集空间类型

基于4类样品的低温氮吸附曲线特征的差异性,建立孔隙模型,探讨不同模型孔隙系统组成及储集空间类型。

1) 孔隙模型I。样品取自南山矿,其低温氮吸附曲线特征为吸附和脱附曲线相对平行,表明煤储层孔隙主要以开放式的透气孔为主,包括一端封闭的圆筒形孔、一端封闭的平行板状孔或尖劈形孔。孔径分布呈双峰形态(图3a),第1个峰值出现在3~4 nm处,第2个峰值出现在20~30 nm处(图3b)。该类型孔隙系统的比表面积一般较小,一般

表1 鹤岗煤田煤岩组分及孔隙结构参数

Table 1 Coal component and pore structure parameters of Hegang Coalfield

矿区	样品编号	兰氏体积/ $(\text{m}^3 \cdot \text{t}^{-1})$	平均孔径/nm	比表面积/ $(\text{m}^2 \cdot \text{g}^{-1})$	总孔体积/ $(\text{mL} \cdot \text{g}^{-1})$	灰分/%	镜质组含量/%	孔隙所占比例/%			孔隙度/%
								微孔	小孔	中孔	
益新矿	YS1	13.53	13.530	1.397	0.00473	15.17	85.2	65.92	25.60	8.48	3.52
	YS2	17.15	11.830	1.273	0.00377	10.87	92.4	64.60	29.03	6.37	4.34
乌山矿	NS1	25.64	13.370	0.544	0.00181	13.56	91.4	71.56	20.71	7.73	4.87
	NS2	21.46	15.830	0.781	0.00309	8.92	94.1	60.23	29.29	10.48	2.73
	NS3	22.54	14.610	1.054	0.00385	13.34	92.9	61.99	27.58	10.43	3.86
	NS4	21.81	12.090	1.553	0.00469	8.21	81.6	68.17	26.31	5.52	5.45
南山矿	N1	20.78	12.130	0.689	0.00331	7.93	53.5	56.4	27.35	16.25	5.12
	N2	21.17	10.230	2.027	0.00365	9.29	71.1	60.9	19.97	19.13	3.16
	N3	20.54	13.160	0.192	0.00280	5.48	72.3	47.7	26.20	26.10	5.31
	N4	20.15	15.310	0.956	0.00286	6.31	68.4	56.7	25.70	17.60	3.96
兴安矿	XA1	25.52	9.140	3.090	0.00940	35.26	30.9	75.1	17.80	7.10	1.22
	XA2	26.43	6.770	3.628	0.00823	36.14	52.8	80.4	13.90	5.70	0.77
	XA3	27.8	5.290	4.105	0.00973	35.28	48.7	89.3	7.70	3.00	1.05
	XA4	25.18	5.140	2.710	0.00719	26.75	61.7	81.5	13.20	5.30	2.34
峻德矿	JD1	20.92	88.752	2.537	0.00537	25.47	64.7	94.5	4.40	1.10	2.55
峻德矿	JD2	23.83	5.935	2.776	0.00496	27.22	68.7	92.7	3.50	3.80	0.94
峻德矿	JD3	24.42	6.547	2.855	0.00548	24.89	70.3	89.3	5.70	5.00	1.59
峻德矿	JD4	21.77	10.260	2.078	0.00606	20.69	78.1	93.3	4.10	2.60	1.74
峻德矿	JD5	20.66	13.190	2.546	0.00528	23.75	75.9	87.7	88.20	4.10	1.38

在  $1 \text{ m}^2/\text{g}$  以下, 平均孔径为  $14.7 \text{ nm}$ , 说明小孔和微孔均对比表面积贡献相当, 该类孔隙吸附能力弱, 解吸能力强。镜下观察发现镜质组中气孔成群聚集(图3c), 孔径分布范围大, 部分孔隙边缘呈爆炸状, 连通性差, 孔内没有充填物。裂隙多为煤岩变质过程中形成的缩聚裂隙(图3d), 长度较短、形状无序, 对改善煤岩的渗透性意义较小。

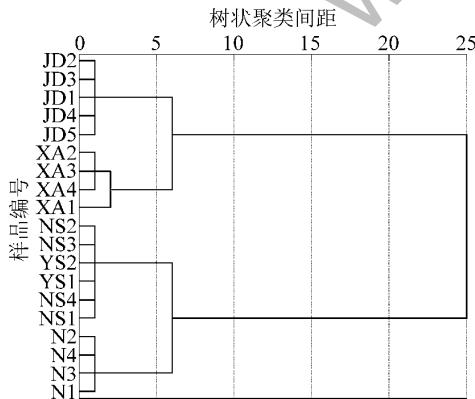
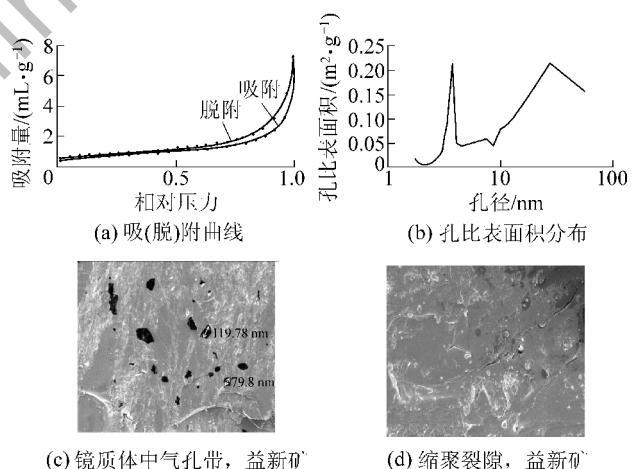


图2 鹤岗煤田各矿区样品孔隙结构参数与组分Q型聚类谱系图

Fig. 2 Q type cluster of coal component and pore structure parameters of Hegang Coalfield

图3 模型I孔隙结构及微观储集空间特征  
Fig. 3 Characteristic of pore structure and microscopic reservoir space in Model I

2) 孔隙模型II。样品来自益新矿和乌山矿, 与模型I的区别在于该类型孔隙的低温氮吸附曲线在相对压力0.5附近出现滞后环(图4a), 说明孔隙形态逐渐多样化, 出现两端开口的圆筒孔和四边都开口的平行板状孔。煤样的比表面积增加, 范围介于 $0.8 \sim 1.5 \text{ m}^2/\text{g}$ , 平均孔径为 $13.5 \text{ nm}$ , 可知小孔的数量在下降(图4b), 其对比表面积的贡献随之减小,

该类孔隙吸附能力较好。孔隙仍然以气孔为主(图4c) 裂隙以张性裂隙为主,表现为多条弯曲、折线裂隙相交(图4d),延伸范围较大,对渗透性起到一定作用。

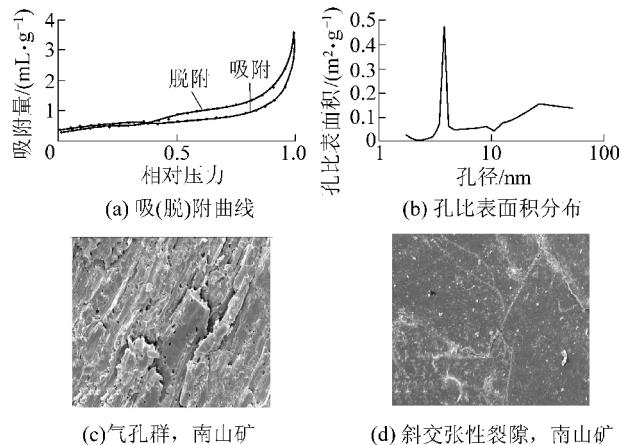


图4 模型II孔隙结构及微观储集空间特征

Fig. 4 Characteristic of pore structure and microscopic reservoir space in Model II

3) 孔隙模型III。峻德矿煤样的吸附、脱附曲线与模型II较为相似,区别为吸附脱附曲线完全分开(图5a)。比表面积为 $2\sim3\text{ m}^2/\text{g}$ ,平均孔径在8 nm左右。孔隙系统比表面积主要来自微孔(图5b、图5c)。小孔仍然占有一定比例。张性裂隙(图5d)的数量和开启程度都在增加,对煤层气的吸附和扩散都十分有利。

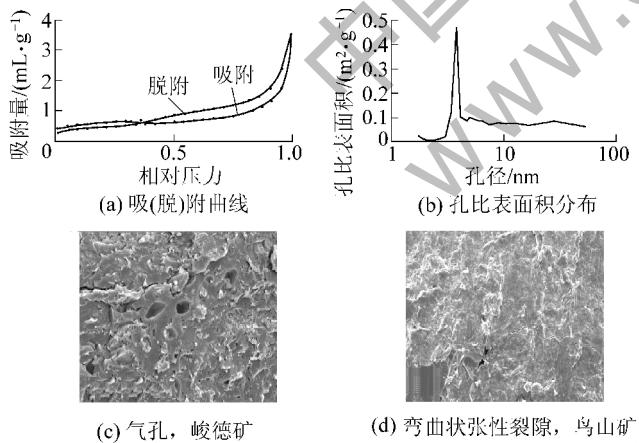


图5 模型III孔隙结构及微观储集空间特征

Fig. 5 Characteristic of pore structure and microscopic reservoir space in Model III

4) 孔隙模型IV。煤样来自兴安矿,其吸附和脱附曲线的特点是在相对压力为0.5处存在突出的拐点(图5a),这是由于肚大口小的“瓶型微孔”大量发育导致的。该煤样的比表面积最大,基本在3

$\text{m}^2/\text{g}$ 以上,平均孔径6.5 nm,这是由于比表面积全部来自微孔。微孔具有较大的比表面积(图6b)。该类型孔隙具有较强的吸附能力,但是解吸难度较大。煤样还可见面与面之间滑动或摩擦形成的摩擦孔,与气孔伴生,形状为不规则圆形,边缘多为锯齿状,呈定向排列与擦痕方向垂直(图6c)。张性裂隙在一定范围内相互交错,形成网状规模(图6d),是所有模型中扩散能力最强的。

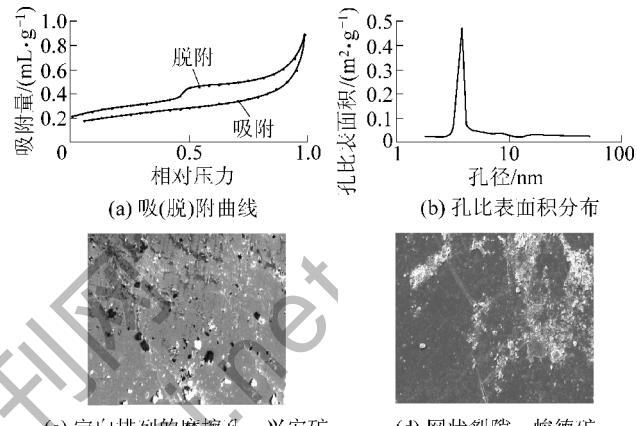


图6 模型V孔隙结构及微观储集空间特征

Fig. 6 Characteristic of pore structure and microscopic reservoir space in Model V

## 2.3 煤相类型分析

GI-TPI图解是目前应用较为广泛的煤相分析方法,通过凝胶化指数(GI)和结构保存指数(TPI)判断煤岩的形成环境。凝胶化指数反映古泥炭沼泽的水位变化特征。结构保存指数表示泥炭沼泽的埋藏速度和基底沉降速度<sup>[17-19]</sup>。由图7可以看出,煤田南部的MSC4期成煤环境为潮湿森林沼泽,向北过渡为较浅覆水沼泽和较深覆水沼泽。鹤岗煤田的凝胶指数和结构保存指数均大于1,说明木本植物占有优势,反映出研究区煤层主要形成于陆相背景下的潮湿沼泽环境。同一沉积期鹤岗煤田南部的俊德矿和兴安矿凝胶指数和结构保存指数低于北部的益新矿、鸟山矿和南山矿,表明自南向北水体逐渐加深的沉积环境和沉降速度逐渐增加的埋藏条件。

## 2.4 煤相变化特征

镜/惰比( $V/I$ )、灰分( $A_d$ )和全硫含量( $S_{t,d}$ )常用来分析成煤环境<sup>[20]</sup>。镜/惰比值可以反映成煤过程中泥炭遭受氧化的程度。灰分是对沼泽覆水深度和水动力条件描述的参数。全硫含量代表沼泽水体的氧化还原程度。由图6可以看出,煤田自南向北镜/惰比值升高,灰分不断减少,硫含量

与灰分趋势相似。这是由于煤田北部埋藏速度较快和覆水较深导致,而南部由于邻近物源和水动力较强的原因,使得灰分较高。从岩性组合(图7)也可以看出煤田南部粗粒沉积较多,向北逐渐变细,说明北部的成煤环境较好,易形成分布稳定的厚煤层。

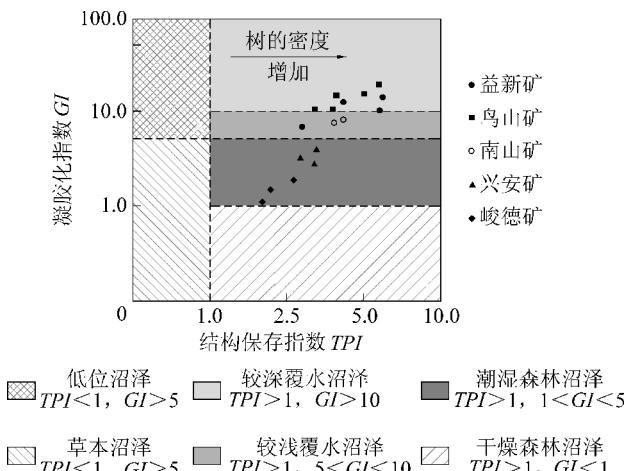


Fig. 7 TPI-GI facies diagram of coal seams in Hegang Coalfield

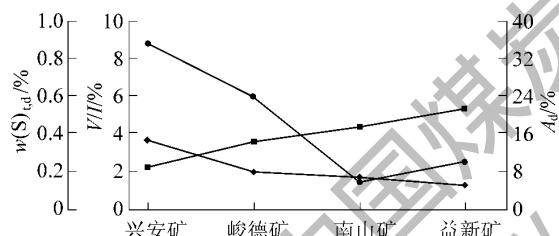


Fig. 8 Comparison of coal facies parameters in Hegang Coalfield

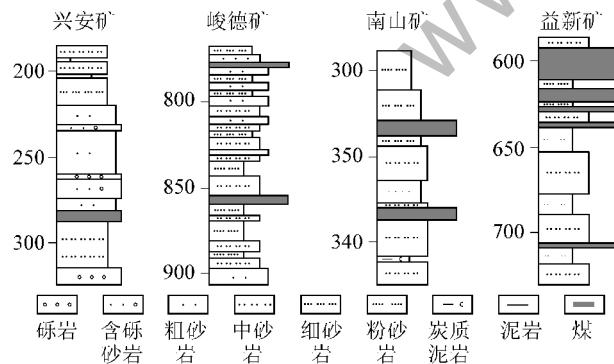


Fig. 9 Characters of lithological association in Hegang Coalfield

## 2.5 聚煤环境分析

充分利用油田钻井和煤田钻孔资料对鹤岗煤田城子河组沉积环境进行分析,认为该时期发育5个完整的中期旋回,而城中段是重要的聚煤期。前人

指出鹤岗煤田存在冲积扇、辫状河、曲流河、扇三角洲等多种沉积体系,本次研究认为扇三角洲沉积体积是城中段主要的聚煤环境。MSC4期盆地稳定、持续沉降,使得可容空间增加速率与泥炭沉积速率相对平衡,利于形成一定厚度、相对稳定和连续的煤层。该时期物源方向为峻德矿和兴安矿,通过辫状河道向东北方向延伸,泛滥平原相的分布范围不断扩张,水体自南向北逐渐加深,与煤相分析结果一致。此时,大面积沼泽环境为聚煤提供良好的物质基础,形成5个聚煤区(图10),煤田自南向北聚煤区的数量和面积都在增加。

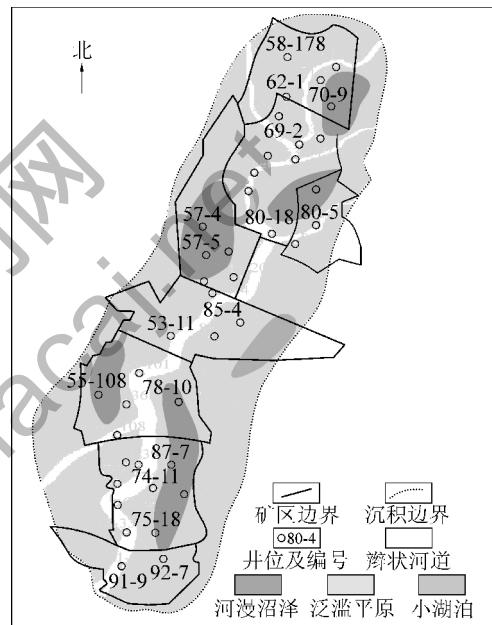


图10 鹤岗煤田 MSC4 上升半旋回沉积相图

Fig. 10 Diagram of deposition facies of half rising base level cycles in MSC4 stage of Hegang Coalfiled

## 3 沉积环境对应的储层物性差异讨论

### 3.1 沉积环境对孔隙的影响

沉积环境通过影响煤岩组分从而实现控制其孔隙发育程度和吸附能力<sup>[21-23]</sup>。煤岩组分中灰分含有特殊意义,这是由于煤中灰分来源于矿物质,其含量可以客观反映矿物质含量的高低。通过灰分和煤岩孔隙度关系发现,二者具有一定的负相关关系,说明灰分对孔隙发育具有控制作用。产生上述现象的原因是南部矿区主要发育扇三角洲沉积,物源由南部注入煤田,水体向北逐渐加深。南部矿区距离物源较近,水动力强,煤中矿物质含量高,使得灰分随之增加,导致煤岩孔隙被灰分充填,最终孔隙系统复杂化(图11)。

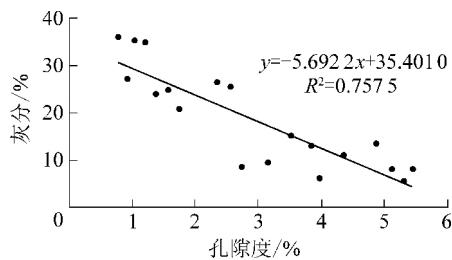


图 11 鹤岗煤田灰分与孔隙度的关系

Fig. 11 Diagram of ash content and porosity in Hegang Coalfield

### 3.2 沉积环境对裂隙的影响

割理是煤层中常见的内生裂隙系统,它经过煤化作用和构造等复合地质过程形成的天然裂隙。通常划分为相互垂直的2组,面割理一般连续性好,是主要的裂隙。端割理连续性差,受面割理控制。根据煤岩样品统计面割理发育情况进行排序(图12)。

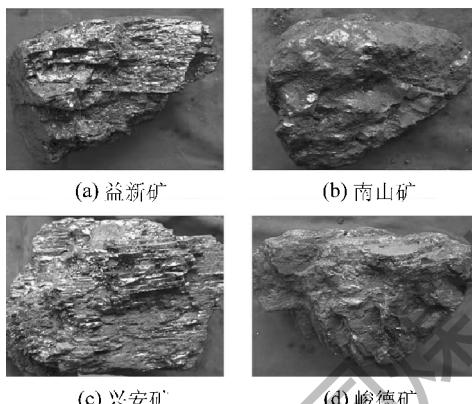


图 12 鹤岗煤田煤岩标本照片

Fig. 12 Photo of coal sample in Hegang Coalfield

兴安矿最为发育,其次为峻德矿,再次为益新和鸟山矿,南山矿最末。煤岩裂缝发育程度与成煤环境有着密切的关系,水体的稳定程度和成煤物质的埋藏速度将直接影响裂缝发育程度。结构保存指数(TPI)可用来分析成煤环境相关信息,TPI越高说明植物保存结构越好,水动力条件越弱,如图13所示。

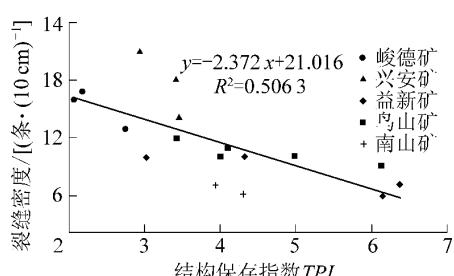


图 13 结构保存指数与裂隙关系

Fig. 13 Relationship of TPI and crack

由图13可以看出,TPI与裂隙发育成反比,由

于兴安矿、峻德矿区成煤环境水体动荡,在泥炭成岩过程中易发生层间滑动,导致裂隙的规模和延伸范围也有所增加。煤田北部水动力变弱,裂隙数量相应减少。

## 4 结 论

1) 通过对鹤岗煤田孔隙结构特征进行聚类分析,建立4种孔隙模型,分别对应不同矿区。鹤岗煤田孔隙以微孔为主,小孔次之,整体吸附能力较强,但不同孔隙模型之间对煤层气解吸和渗流的影响存在明显差异。孔隙模型I中气孔相对独立,易解吸但渗流能力差。孔隙模型II、III和IV吸附能力相对较强,但后两者网状裂隙更为发达,对改善渗透率意义重大,利于煤层气产出。

2) 鹤岗煤田南部煤相为森林沼泽,向北过渡为较浅覆水沼泽和较深覆水沼泽。煤田自南向北镜/惰比值具有增大趋势,灰分和全硫含量反之,反映出埋藏速度加快和覆水加深的成煤环境。扇三角洲平原是城中段主要聚煤环境,物源从煤田南部注入,通过辫状河道向东北延伸,使得煤田北部矿区易形成稳定厚煤层。

3) 沉积环境对煤层孔隙结构和裂隙发育产生一定的控制作用。鹤岗煤田由南向北,水体逐渐加深,煤岩孔隙模型由IV向I逐渐过渡,岩性组合由粗变细,灰分含量降低。灰分含量高导致部分孔隙遭到充填,使得孔隙系统多元化、复杂化;南部水动力逐渐增强,邻近物源,动荡的水体使得泥炭在埋藏过程中裂缝的数量和规模逐渐增加。

4) 鹤岗煤田煤层具有北厚南薄的特点,渗流能力和后期改造的可操作性南强北弱。因此在鹤岗盆地寻找有利目标时,需要综合考虑宏观构造背景和微观显微特征。

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