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王朝引.基于陆相沉积控制的主充水含水层富水性三维展布特征[J].煤炭科学技术,2020,48(12):198-204. doi: 10.13199/j.cnki.est.2020.12.025
WANG Chaoyin.Three dimensional distribution characteristics of water-richness of main water filling aquifers based on continental sedimentary [J]. Coal Science and Technology, 2020, 48 (12) : 198 - 204. doi: 10.13199/j.cnki.est.2020.12.025

基于陆相沉积控制的主充水含水层富水性三维展布特征

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摘要:鄂尔多斯盆地北部属于中生代陆相沉积,受毛乌素沙漠降水入渗强、松散层储水空间大等因素控制,在蒙陕接壤的深埋煤田区形成了“水压高、水量大、富水不均一”的煤层顶板主充水含水层。为查清该含水层富水性空间展布特征,以纳林河二号煤矿为研究对象,采用沉积相分析法开展了层序地层格架、岩石粒径分布、砂泥岩空间展布等研究,采用音频电穿透技术对工作面顶板含水层三维结构特征进行了探测,并利用井下疏放水钻孔对物探结果进行了检查验证,结果表明:纳林河二号矿井延安组三段中上部发育真武洞砂岩,厚5~20 m,连续性好;直罗组一段平行不整合于延安组之上,厚70~90 m,底部七里镇砂岩厚5~23 m,连续性好,自然伽马曲线值低;延安组三段和直罗组一段是3-1煤开采的主充水含水层。延安组和直罗组砂岩含水层受河流相沉积控制,含水层富水性在三维空间上呈条带状分布,其中延安组三段沿北东—南西方向展布,富水性由东南向西北逐渐减弱;直罗组一段沿北北西—南南东方向展布,古河道中心砂地比为0.4~0.7,富水性由西北向东南逐渐减弱,矿井中部富水性相对较强。延安组和直罗组含水层富水区呈北东—南西和北西—南东交叉分布,由于直罗组早期河流回春,水动力条件增强,在直罗组底部发育了曲流河沉积形成的灰绿色、青灰色(含砾)中—粗长石砂岩含水层,导致直罗组含水层整体富水性较延安组含水层强,且与延安组含水层具有垂向连通性。音频电穿透三维探测确定重点异常区,31101工作面顶板钻孔涌水量(>100 m³/h)和水压均较大,31116工作面顶板含水层富水性分布特征也与物探探测结果吻合,证明纳林河二号井田范围内煤层顶板含水层富水性存在区域性差异,单个工作面范围内也存在含水层富水异常区。

关键词:富水性;三维展布特征;沉积相;音频电穿透技术

中图分类号:TD985 **文献标志码:**A **文章编号:**0253-2336(2020)12-0198-07

Three dimensional distribution characteristics of water-richness of main water filling aquifers based on continental sedimentary

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Abstract:The northern Ordos Basin belongs to the Mesozoic continental deposit,which is controlled by the factors such as strong rainfall infiltration in Maowusu Desert and large water storage space of loose layer.In the deep buried coalfield area adjacent to Inner Mongolia and Shaanxi, the main water filling aquifer of coal seam roof with "high water pressure,large water volume and uneven water rich" has been formed.In order to find out the spatial distribution characteristics of water abundance of the aquifer,taking the No.2 Coal Mine of Nalinhe as the research object,the sequence stratigraphic framework,rock particle size distribution,sand and mudstone spatial distribution were studied using sedimentary facies analysis method, and the three-dimensional structural characteristics of the roof water bearing layer of the working face were detected by audio frequency electric penetration technology, and the geophysical exploration results were carried out using the underground drainage boreholes inspection and verification.The results showed that Zhenwudong sandstone was developed in the middle and upper part of the third member of Yan'an formation,with a thickness of 5.0~20.0 m and good continuity.The first member of

收稿日期:2020-05-04;责任编辑:郭 鑫

基金项目:国家自然科学基金资助项目(41302214);中煤科工集团西安研究院有限公司创新基金面上资助项目(2018XAYMS03)

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Zhiluo formation was parallel unconformity on the Yan'an formation, with a thickness of 70.0~90.0 m. The Qilizhen sandstone at the bottom of Zhiluo formation was 5.0~23.0 m thick, with good continuity and low value on the natural gamma curve. The sandstone aquifers of Yan'an formation and Zhiluo formation were controlled by fluvial facies deposition, and the water abundance was distributed in strips. The third member of Yan'an formation was distributed along NE-SW direction, and the water abundance was gradually weakened from southeast to northwest; the first member of Zhiluo formation was distributed along the north-south direction, and the sand to land ratio in the center of the ancient channel is 0.4~0.7. The water abundance was gradually weakened from northwest to southeast, and the water abundance in the middle of the mine was relatively strong. The aquifer rich areas of Yan'an formation and Zhiluo formation were distributed in northwest southeast and northeast southwest. The overall water yield of Zhiluo formation was stronger than that of Yan'an formation, and has vertical connectivity with Yan'an formation aquifer. In the key abnormal area determined by audio frequency electric penetration three-dimensional detection, the water inflow ($>100 \text{ m}^3/\text{h}$) and water pressure of 31101 working face roof are relatively large, and the distribution characteristics of water abundance of roof aquifer in 31116 working face are also consistent with the results of geophysical exploration, which proves that there are regional differences in water abundance of coal seam roof aquifer within the scope of No.2 Minefield of Nalinhe, and there is also water rich difference of aquifer within the scope of single working face normal area.

Key words: aquifer water richness; three dimensional distribution characteristics; sedimentary; audio frequency electrical penetration technology

0 引言

鄂尔多斯盆地是中生代燕山运动形成的大型内陆坳陷^[1-3],在侏罗世早期(延安组)由于构造条件较稳定和源区粗粒碎屑供应相对贫乏,形成了禀赋最为优异的煤炭资源^[4-5]。但是多沉积旋回作用下,在侏罗纪煤层顶板形成了砂泥岩互层结构^[6],尤其是地层抬升、河流回春阶段,发育了粗粒较大、层段较厚的砂岩段,在长期的地下水运移过程中,成为主要的富水含水层^[7-10],其空间展布的复杂性、储水条件的宏观与微观非均质性、地下水空间分布的多样性,一直是该区域水文地质条件、地下水系统结构研究的重点,也是煤矿水害防治、地下水资源勘查开发的最大障碍。蒙陕矿区位于鄂尔多斯汇水盆地腹部,顶板含水层受河流相沉积控制,厚度大、结构复杂、水压大、富水性强且不均^[11-15],例如新街矿区首采工作面钻孔水量均 $<10 \text{ m}^3/\text{h}$,而呼吉尔特和纳林河矿区钻孔涌水量则普遍 $>60 \text{ m}^3/\text{h}$,复杂的地质和水文地质条件导致多种灾害并存^[16-18],其中纳林河二号矿是本地区最早开工建设的大型现代化矿井,为了查清该矿存在的水文地质问题,提出科学合理的防治水对策,前人主要从层序地层格架、安全开采主控因素^[18]、水文地质参数灵敏度^[19]、水文地球化学特征^[20]、水害防治技术等方面开展了大量研究,建立了宏观尺度上煤层顶板三维地质结构^[18],并进行了涌水量预测^[19,21],但未将地质沉积和水文地质赋存有机联系,也未开展井田和工作面尺度的主充水含水层富水性三维展布特征方面的研究。基于此,采用沉积相分析、音频电穿透、钻孔揭露等方法,分析含水层沉积环境和不同沉积相中砂岩的发育程度、孔隙度等,并基于陆相沉积控制规律,探究

主采煤层顶板延安组和直罗组含水层富水性及三维空间展布特征。

1 研究区概况

纳林河二号矿井位于内蒙古自治区鄂尔多斯市乌审旗境内,具有高原沙漠地貌特征,地表均被第四系风积沙所覆盖,多为新月形或波状沙丘,没有基岩出露,降水入渗能力强,松散层储水空间大^[22]。区内植被稀疏,为半荒漠地区。无定河由西向东流经井田中南部,井田北部发育其支流纳林河,南部发育其支流臭河沟。年降水量 194.7~531.6 mm,平均 396.0 mm;年蒸发量 2 297.4~2 833.0 mm,平均 2 534.2 mm,年蒸发量为年降水量的 5~7 倍。

受沉积环境和沉积相控制,纳林河二号井田内主要发育第四系萨拉乌苏组孔隙潜水含水层、白垩系志丹群承压水含水层、侏罗系直罗组承压水含水层和延安组承压含水层。在各地层中,分布着厚度较大且范围广的泥岩、粉砂质泥岩及泥质粉砂岩等,为各承压含水层之间的良好的隔水层。3-1 煤层为全区可采煤层,3-1⁺煤层为 3-1 煤层在井田西部及南部的上分层;另外,井首采工作面导水裂缝带实测高度 103.2 m,煤炭开采过程中导水裂缝带可发育至直罗组一段,因此延安组三段真武洞砂岩和直罗组一段七里镇砂岩是煤炭开采的主充水含水层。

2 含水层沉积相特征

沉积相是沉积物的形成环境、生成条件和其特征的总和,不同沉积环境中形成的砂体,其岩石成分、结构、形态、展布特点不同,相的蓄水空间和水力性质有很大差别,沉积相对地下水分布和储集具有重要的控制作用。

2.1 沉积相基本参数特征

纳林河二号矿井延安组三段的岩石基本色调为灰白色、灰色,主要由浅灰色、灰白色各粒级长石砂岩,灰色、深灰色砂质泥岩、泥岩和煤层组成,指示其形成于河流环境和湖泊三角洲泥炭沼泽环境。直罗组一段由灰绿色、青灰色(含砾)中-粗长石砂岩(俗称“七里镇砂岩”),局部夹粉砂岩、砂质泥岩组成;二段由灰绿色砂质泥岩、泥岩与灰绿、黄绿色粉砂岩、细粒长石砂岩(俗称“高桥砂岩”)互层组成。该

岩石组合特征预示其形成环境经历了曲流河向湖泊三角洲环境的转变。依据 SY/T 5434—2009《碎屑岩粒度分析方法》对3-1煤层以上延安组和直罗组碎屑岩粒度进行分析,发现2个岩段的碎屑岩粒度曲线均呈两段式^[23]。3-1煤层以上延安组和直罗组的碎屑岩之粒度曲线均呈两段式(图1),反映了其形成环境的水动力条件较弱,碎屑颗粒主要以跳跃状和悬浮状为主的搬运方式,缺少推移滚动的载荷。

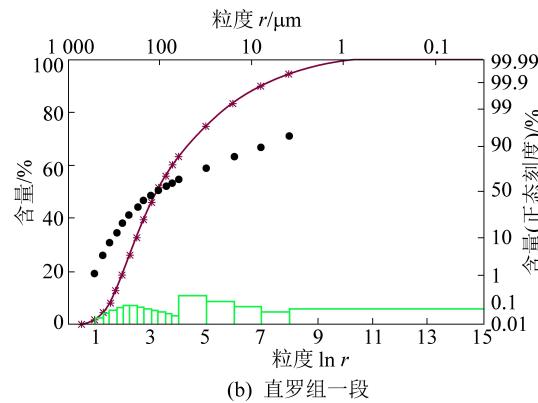
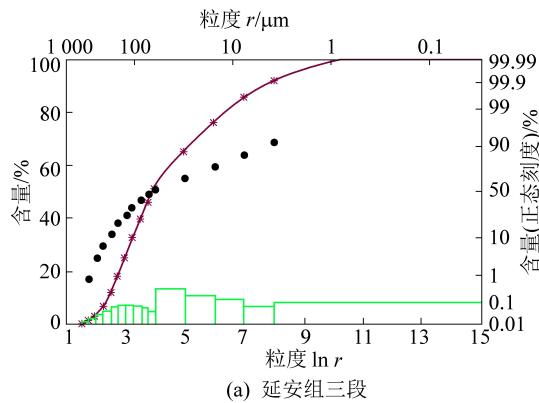


图1 煤层顶板砂岩粒径分布

Fig.1 Grain size distribution of sandstone in coal seam roof

2.2 沉积相多孔对比

以纳林河二号井田中部为研究区域,剖面上钻孔由南西向北东依次有MD35、MD33、MDBS5、NL32、MD15、NL22、MD11、NL11等共8口井。该剖面上(图2),地层自下而上分别为3-1煤层、延安组三段、直罗组一段、直罗组二段和安定组,向西缓倾

斜。其中,3-1煤层厚2~6 m,自西向东逐渐变厚;延安组三段厚80~110 m,平均90 m,其中砂体厚2~25 m,平均9 m,主要砂体(真武洞砂岩)位于该部分地层中上部,厚5~20 m,连续性比较好。直罗组一段平行不整合于延安组之上,厚70~90 m,平均80 m。底部七里镇砂岩厚5~23 m,连续性比较好,

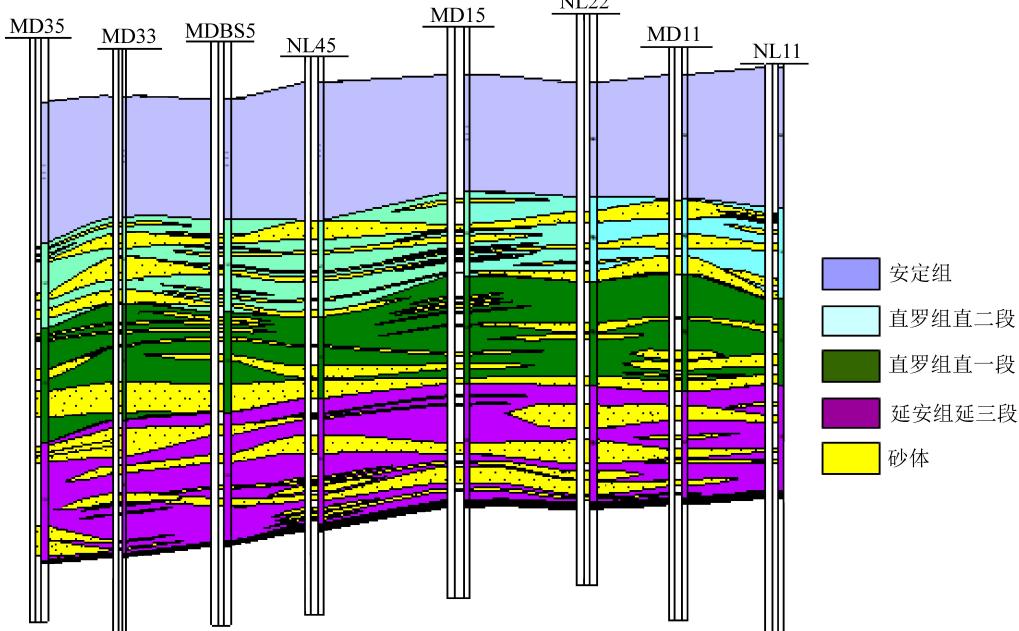


图2 MD35井-NL11井地层对比图(SW-NE)

Fig.2 Stratigraphic correlation map of MD35 - NL11 holes

自然伽马曲线值低。整个直罗组一段砂体层数量较少,单层厚度2~23 m。直罗组二段与一段呈整合接触,厚60~80 m,平均75 m。底部高桥砂岩较薄,厚3~14 m,自然伽马曲线上表现为低。总体而言,直罗组二段的砂体个数比较多,单个砂体厚度1~20 m,比较薄。安定组整合于直罗组之上,厚度90~110 m,平均95 m,其下部普遍沉积一套砂质泥岩,在自然伽马曲线上呈高值。

3 基于沉积相的富水性分析

3.1 基于沉积特征的富水性分区

纳林河二号矿井主采的3-1煤层直接充水含水层为延安组三段和直罗组一段砂岩含水层。其中,延安组三段分布具有北厚南薄的态势,最厚处可达117.7 m,最薄处仅为54.2 m,平均83.5 m;直罗组一段在区内东北部地层厚度变化较大,中部地区多发育多个小型凹陷,南部地层厚度比较稳定厚度,最厚可达130.7 m,最薄仅49.6 m,平均76.3 m。直罗组一段在区内与延安组三段呈平行不整合接触。根据含水层沉积环境和不同沉积相中砂岩的发育程度、孔隙度、井田断层等因素,通过公式(1)对3-1煤层至直罗组之间含水层富水性进行分区^[5-7],

$$Z_i = s_i a_1/x_1 + h_i a_2/x_2 + \varphi_i a_3/x_3 \quad (1)$$

式中: Z_i 为第*i*钻孔所在的富水性指标; s_i 、 h_i 和 φ_i 分别为第*i*钻孔所在沉积亚相(微相)、第*i*钻孔中单层砂岩厚度和第*i*钻孔内研究对象砂地比对应的富水性分区指标赋值, a_1 、 a_2 和 a_3 分别为该钻孔沉积亚相(微相)、各单层砂岩厚度和相应砂地比的权重; x_1 、 x_2 、 x_3 为等对应的级化系数。

经过征求专家意见和综合分析, s_i 、 h_i 、 φ_i 赋值见

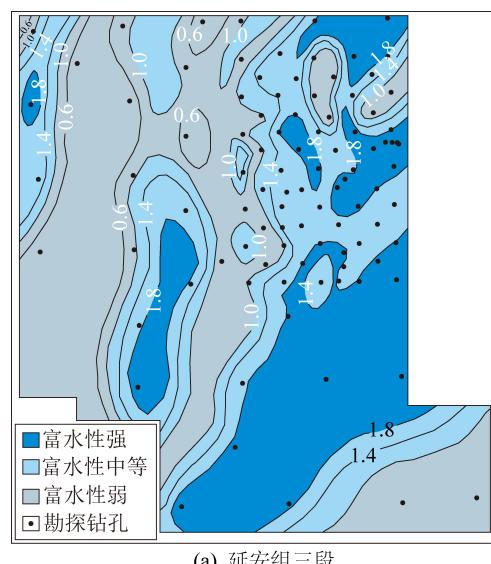


表1、表2、表3。

表1 沉积亚相(微相)对应富水性分区指标赋值

Table 1 Water abundance zoning index assignment for sedimentary (subfacies) microfacies

| 沉积相 | 沉积亚相 | 沉积微相 | s_i |
|--------|------|------|-------|
| 辫状河相 | 河道砂坝 | 边部 | 0.3 |
| | | 冀部 | 0.5 |
| | | 中心 | 0.7 |
| 曲流河相 | 河道砂坝 | 边部 | 0.2 |
| | | 冀部 | 0.4 |
| | | 中心 | 0.6 |
| 三角洲平原相 | 分流河道 | 边部 | 0.4 |
| | | 冀部 | 0.6 |
| | | 中心 | 0.8 |

表2 单层砂体对应富水性分区指标赋值

Table 2 Water abundance zoning index assignment for single layer sand body

| 单层砂体厚度/m | h_i |
|----------|-------|
| <5 | 0.2 |
| ≥5~10 | 0.4 |
| ≥10~20 | 0.6 |
| ≥20 | 0.8 |

表3 砂地比对应富水性分区指标赋值

Table 3 Water abundance zoning index assignment for sand ratio

| 砂地比 | φ_i |
|----------|-------------|
| <0.3 | 0.3 |
| ≥0.3~0.5 | 0.4 |
| ≥0.5 | 0.5 |

征求专家意见并作归一化处理后,沉积亚相的权重为 $a_1=0.3623$,单层砂体厚度的权重为 $a_2=0.3325$,砂地比的权重为 $a_3=0.3052$ 。等级化学系统 $x_1=0.3706$, $x_2=0.3298$, $x_3=0.2996$ 。

以钻孔为坐标点,按照目标路段的综合量化指数 Z_i ,分别以 $Z_i=1.0$ 、 $Z_i=1.8$ 为限值,将井田富水性划分为弱富水($Z_i<1.0$)、中等富水($1.0<Z_i<1.8$)和强富水($Z_i>1.8$)3个等级,绘制综合富水性分区图(图3)。

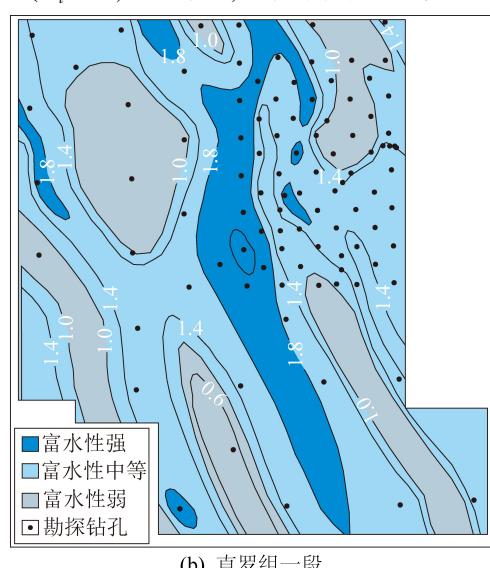


图3 3-1煤顶板砂岩富水性分区

Fig.3 Division map of water richness of sandstone in 3-1 coal seam roof

3-1煤顶板延安组砂岩含水层富水性沿北东—南西方向呈条带状分布特征(图3),富水性由东南向西北逐渐减弱;直罗组一段砂岩含水层富水性沿北北西—南南东方向呈条带状分布特征,富水性由西北向东南逐渐减弱,矿井中部富水性相对较强。

3.2 富水性分布特征

利用不同勘探时期的钻孔资料,对井田东部(图3)延安组和直罗组含水层富水性进行了三维空间分布特征研究,得到了3-1煤顶板延安组和直罗组含水层富水性在三维空间上的整体分布特征(图4和图5):①3-1煤顶板延安组和直罗组含水层富水区呈北西—南东和北北西—南南东向交叉分布,其中延安组三段为三角洲平原向河流相演变时期,以分流河道、漫滩沼泽以及决口扇为主,是井田范围内规模最大的古河道;直罗组一段为辫状河沉积,沉积亚相有河床和泛滥平原,古河道斜穿井田,古河道中心砂地比为0.4~0.7,河床规模大;②研究区在延安组和直罗组时期,总体上属于河流相沉积,受到主河道、分流河道、漫滩等控制,导致沉积过程中砂体呈条带状分布,由此控制3-1煤顶板延安组和直罗组含水层富水性呈条带状分布;③直罗组早期,由于河流回春,水动力条件增强,在直罗组底部发育了曲流河沉积形成的灰绿色、青灰色(含砾)中—粗长石砂岩含水层(七里镇砂岩)^[21];而延安组三段沉积的砂岩段(真武洞砂岩)属于正常的小沉积旋回,在砂岩粒径、厚度等方面,均远小于七里镇砂岩段,导致了3-1煤顶板直罗组含水层整体富水性较延安组含水层强;④同样由于直罗组早期强水动力条件下,河流对延安组地层的切割剥蚀,使得直罗组一段砂岩层与延安组三段砂岩层在局部相连,导致3-1煤顶板延安组和直罗组含水层富水性局部具有垂向连通性。

4 富水性精细化探测结果分析

4.1 物探探测

应用音频电穿透三维探测技术,在31116工作面顶板上方共探测发现5处异常区(图6):1号异常区主要分布在顶板上40~120 m,分布范围较小,异常条带性相对较弱,整体异常幅值相对较弱;2号

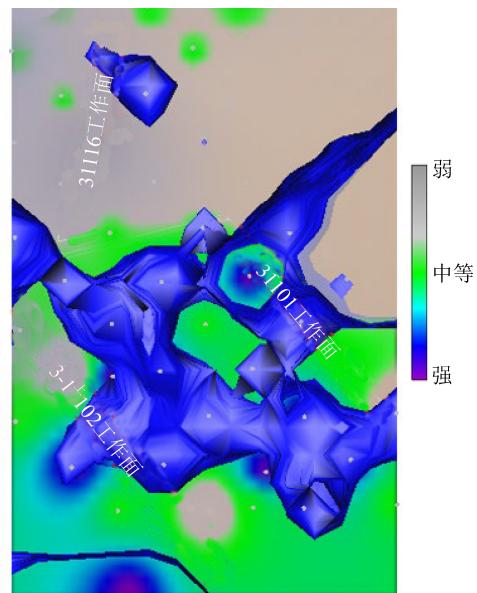


图4 3-1煤顶板含水层富水性分布俯视
Fig.4 Top view of water richness division of coal seam roof aquifer

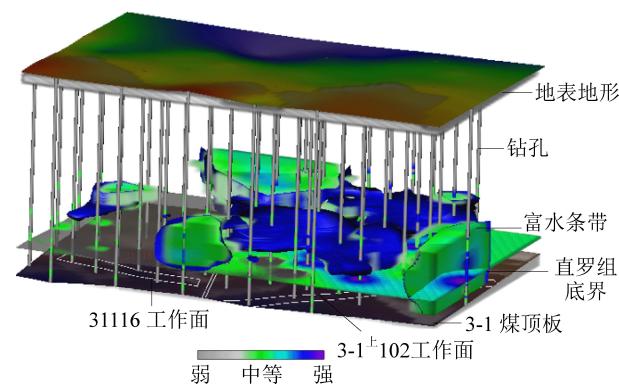


图5 顶板砂岩含水层富水性空间展布
Fig.5 Spatial distribution of water richness of roof sandstone aquifer

异常区主要分布在顶板上40~120 m,分布范围较小,异常条带性相对较弱,异常中心位于运输巷顶板上方120 m附近,整体异常幅值相对中等;3号异常区主要分布在顶板上60~120 m,分布范围较小,异常条带性相对较弱,整体异常幅值相对较弱;4号异常区主要分布在顶板上80.0~120.0 m,分布范围较小,异常条带性相对较强,异常幅值相对较强;5号异常区主要分布在顶板上20~120 m,分布范围较大,异常条带性相对较强,异常幅值相对中等。

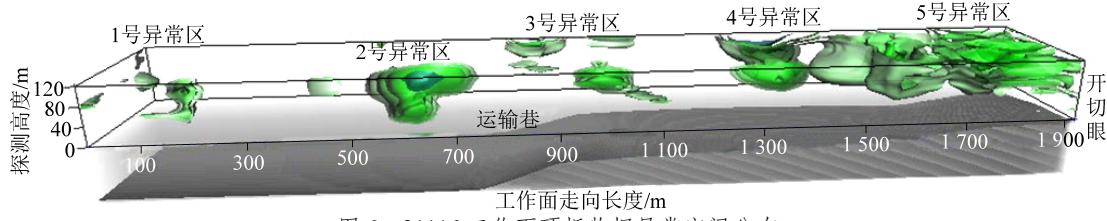


图6 31116工作面顶板物探异常空间分布

Fig.6 Spatial distribution of roof geophysical anomalies in 31116 working face

4.2 钻探探测

基于沉积相研究和物探探测,在31116工作面两顺槽内施工31个探放水钻孔,钻孔终孔水量为 $1.0\sim18.5\text{ m}^3/\text{h}$,平均涌水量 $10.33\text{ m}^3/\text{h}$,通过钻孔终孔水量等值线图(图7)知,整个工作面顶板存在2处主要的富水异常区:1号富水区;该富水区对应

4号异常区,该区域大多数探放水钻孔涌水量均在 $10\text{ m}^3/\text{h}$ 以上,其中Y4-2钻孔涌水量达到 $17.6\text{ m}^3/\text{h}$,为该区域涌水量最大的钻孔;2号富水区:该富水区对应5号异常区,该区域大多数探放水钻孔涌水量均在 $10.0\text{ m}^3/\text{h}$ 以上,其中F1-2钻孔涌水量 $18.5\text{ m}^3/\text{h}$ 为所有疏放水钻孔中水量最大值。

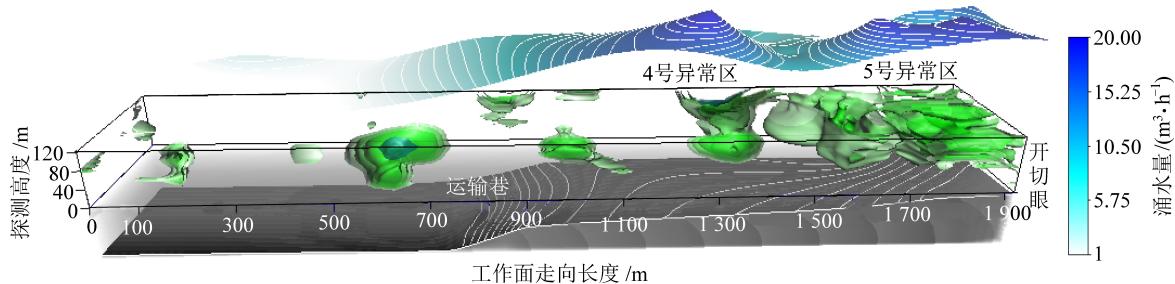


图7 31116工作面顶板物探异常区与疏放水钻孔终孔涌水量分布对比

Fig.7 Comparison between geophysical anomaly area and hole water inflow

31116工作面31个钻孔终孔水压为 $1.2\sim3.3\text{ MPa}$,平均水压力为 1.77 MPa 。如图5—图7所示,通过钻孔终孔水压等值线图可以看出,整个工作面顶板同样存在2处主要的高水压区:1号高水压区:该范围对应前面所分析的1号富水区,钻孔终孔压力均达到 1.8 MPa ,其中Y5-1和Y5-3钻孔终孔水压达到了 2.0 MPa ;2号高水压区:该范围对应前面所分析的2号富水区,钻孔终孔压力多数达到 1.8 MPa ,其中F1-1钻孔终孔水压达到了 3.3 MPa 。综合对比终孔水量、水压和物探异常区的分布对应关系,发现在物探重点异常区(4号和5号异常区)附近,终孔水量、水压均较大。钻探揭露的31116工作面顶板含水层富水性分布趋势与物探探测结果相吻合。

另外,31101工作面184个钻孔终孔水量 $10.4\sim136.6\text{ m}^3/\text{h}$,平均涌水量 $90.8\text{ m}^3/\text{h}$,整个工作面顶板存在2处主要的富水异常区。1号富水区,该异常区在辅助运输巷一侧绝大多数探放水钻孔涌水量均在 $100\text{ m}^3/\text{h}$ 以上,其中Y2-2钻孔涌水量达到 $125\text{ m}^3/\text{h}$,为该区域涌水量最大的钻孔。2号富水区,该范围内回风巷一侧绝大多数探放水钻孔涌水量在 $120\text{ m}^3/\text{h}$ 以上,其中T8-2钻孔涌水量 $136.6\text{ m}^3/\text{h}$ 为所有疏放水钻孔中水量最大值。该现象证明了纳林河二号井田范围内煤层顶板含水层富水性存在区域性差异(如图4和图5),且单个工作面范围内也存在含水层富水异常区。

5 结 论

1) 纳林河二号矿井3-1煤顶板延安组三段和直罗组一段受河流相沉积控制,分别发育了真武洞砂岩段和七里镇砂岩段,平面展布连续性比较好,具

有孔隙率大、渗透性好、富水性强等特点,是3-1煤开采的主充水含水层。

2) 3-1煤层顶板两段充水含水层富水性呈条带状分布,其中延安组3段(真武洞砂岩)沿北东—南西方向展布,富水性由东南向西北逐渐减弱;直罗组一段(七里镇砂岩)沿北北西—南南东方向展布,富水性由北西向南东逐渐减弱,井田中部区域富水性相对较强,表明井田尺度煤层顶板含水层富水性存在显著差异。

3) 3-1煤顶板延安组和直罗组含水层富水区呈北西—南东和北北西—南南东交叉分布,直罗组含水层整体富水性较延安组含水层强,且与延安组含水层具有垂向连通性。

4) 频电穿透三维探测确定的工作面顶板富水异常区,在31101工作面和31116工作面的顶板疏放水钻孔显示水量和水压均较大,证明工作面尺度的顶板含水层富水性分布趋势与物探探测结果相吻合,表明工作面尺度也存在含水层富水性差异。

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