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# 鄂尔多斯盆地南缘黄陵地区煤铀兼探钻孔数据集成与三维地质模型构建

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**摘要：**鄂尔多斯盆地南缘黄陵地区铀成矿前景良好。中国地质调查局在该地区组织实施了含铀岩系三维地质调查工作，以寻找可地浸砂岩型铀矿找矿靶区为目标，采用“煤铀兼探”、“油铀兼探”的新思路，对煤田钻孔资料进行“二次开发利用”，开展勘查选区研究，完成了 354 口煤田钻孔（其中筛选出潜在砂岩型铀矿 (化) 孔 49 口）和 21 口铀矿验证钻孔（其中工业矿 (化) 孔 16 口）的数据采集建库，在此基础上建立了专题成果图集及三维地质模型。该数据库主要由含铀岩系地层厚度等值线图、砂体厚度等值线图、顶底板埋深等值线图、含砂率等值线图、放射性异常等值线图等专题成果图集和三维地质结构模型组成，为铀矿勘探开发提供了有利支撑和服务作用。

**关键词：**砂岩型铀矿；钻孔数据集成；三维地质模型；矿产勘查工程；黄陵地区；鄂尔多斯盆地南缘

**数据服务系统网址：**http://dcc.cgs.gov.cn

## 1　引言

鄂尔多斯盆地是位于华北克拉通的中–新生代大型陆内叠合盆地 (董树文等，2007)，为中国重要的油气、煤、铀等多种能源共存的大型盆地之一 (金若时等，2017；苗培森等，2017a)，其中煤炭资源量高达 2 万亿吨，油气资源总量高达 250 亿吨 (孙玉梅，2018；郑民等，2019)。随着中国经济的快速发展和生态文明建设的需要，铀矿作为重要的新型能源和战略资源，其需求增长越来越快，其中砂岩型铀矿已逐渐成为中国开发的主要铀矿类型之一。2013 年以来，中国地质调查局天津地质调查中心组织实施了“中国主要盆地煤铀等多矿种综合调查评价”等工作，以寻找可地浸砂岩型铀矿找矿靶区为目标，采用“煤铀兼探”、“油铀兼探”的新思路，对煤田、油田钻孔资料进行

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“二次开发利用”，开展勘查选区研究，筛选并圈定有放射性异常的钻孔，优选找矿靶区并进行钻探验证，取得了重要突破 (金若时等，2014；俞礽安等，2019)，在层序地层 (金若时和覃志安，2013；张云等，2016；Jin RS et al.，2018；张天福等，2019)、生物地层 (孙立新等，2017；)、岩石地球化学 (刘晓雪等，2016；张天福等，2016，2018)、铀成矿作用及规律 (苗培森等，2017b；陈印等，2017；冯晓曦等，2017，2019；Jin RS et al.，2019) 等方面积累了大量的研究成果。

本次研究的黄陵地区 (图 1a) 位于鄂尔多斯盆地陕北斜坡南部 (图 1b)，区内构造作用整体较弱，断裂构造不发育，只有一系列北东方向展布的舒缓开阔褶皱。地层产状总体向北西缓倾，倾角小于 5°(陈宏斌等，2006；张岳桥和廖昌珍，2006)。区内黄土覆盖广泛，基岩主要沿深切沟谷出露，自下往上依次为上三叠统延长组 ($T_3y$)(为本区主要的含油气层)，下-中侏罗统延安组 ($J_{1-2}y$)(为本区主要的含煤岩系)，中侏罗统直罗组 ($J_2z$)(为本区主要的含铀岩系) 和安定组 ($J_2a$)，下白垩统洛河组 ($K_1l$) 和环河组 ($K_1h$)。

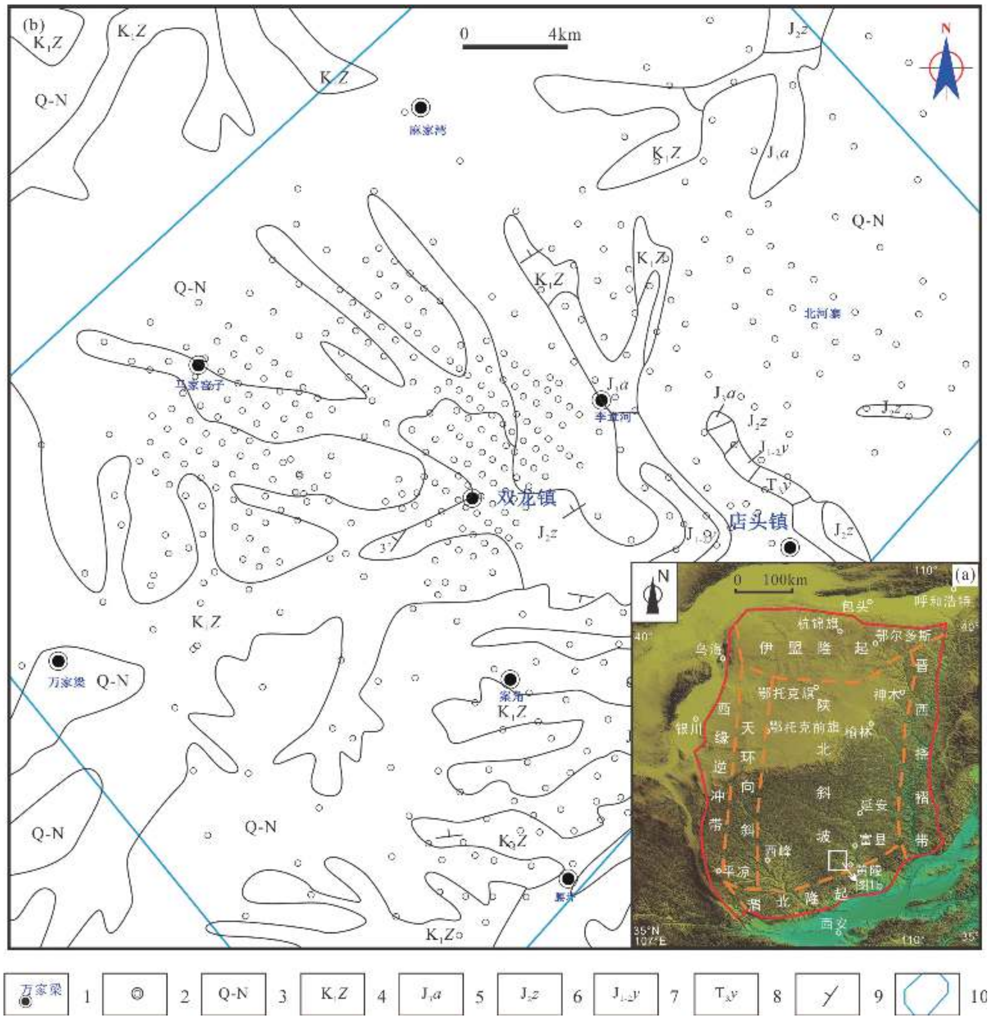

图 1　鄂尔多斯盆地南缘黄陵地区大地构造位置 (a, 构造区划据杨俊杰和裴锡古, 1996) 及钻孔分布图 (b, 底图据陕西省 1：50 万数字地质图数据库❶)

1—地理位置及名称；2—钻孔位置；3—第四系-第三系；4—志丹群；5—安定组；6—直罗组；7—延安组；8—延长组；9—地层产状；10—建模区域

地质钻孔资料作为地下地质情况最真实的信息记录载体，包含了岩性、物性、测井曲线、测试分析、水文等重要的地质信息，可为地质勘探工作的开展提供真实可靠的基础数据支撑。随着大规模区域地质矿产勘查的钻探工作，研究区积累了大量煤田钻孔资料，但多为分散无序的文档和图片资料，无法在行业间实现数据的共享应用，难以发挥数据的价值。随着砂岩型铀矿找矿工作的不断开展，对相关地质资料的集成应用的需求非常迫切 (周小希等，2016)，对其二次开发利用可有效减少地质工作的盲目性和重复工作，极大地提高地质工作效率 (王斌等，2013)。同时，对钻孔数据获取的地质信息进行三维可视化表达，可以更直观地展现各地质体的空间展布及其关系，最大限度地提高地质分析的直观性和准确性，方便勘探工程决策和自动制图，前人也进行了很好的尝试 (向中林等，2009；田小甫等，2012；郁军建等，2015)。

本文工作由国家地质调查项目“北方重要盆地砂岩型铀矿调查与勘查示范”项目支持，首次全面采集了黄陵地区煤田 354 个煤田钻孔资料，按照统一标准整理、扫描、数据类型转换、录入和集成入库，按照 2 km×2 km 控制网度完成数据库建库工作。在此基础上，开展放射性异常钻孔筛查，并结合铀矿钻孔验证，编制了地层厚度等值线图、砂体厚度等值线图、顶底板埋深等值线图、含砂率等值线图、放射性异常等值线图等专题图集，并进一步建立了研究区含铀岩系三维地质结构模型和砂体模型，对铀矿勘探开发提供基础资料支撑。

含铀岩系三维地质调查专题成果图集与三维地质模型数据集 (张云等，2020 ）基本信息如表 1 所示。

**表 1　数据库 (集) 元数据简表**

| 条目 | 描述 |
|---|---|
| 数据库(集)名称 | 鄂尔多斯盆地南缘黄陵地区煤铀兼探钻孔数据集成与三维地质模型构建 |
| 数据库(集)作者 | 张　云，中国地质调查局天津地质调查中心<br>张天福，中国地质调查局天津地质调查中心<br>孙立新，中国地质调查局天津地质调查中心 |
| 数据时间范围 | 2017—2018年 |
| 地理区域 | 108.7648° ~ 109.1581°E，35.5163° ~ 35.8410°N；1 225 $km^2$ |
| 数据格式 | 图集格式为MapGIS (*.wp，*.wl，*.wt)，三维地质模型数据集格式为*.txt |
| 数据量 | 515 Ma |
| 数据服务网址 | http://dcc.cgs.gov.cn |
| 基金项目 | 国家重点研发计划(2018YFC0604200)、国家重点基础研究发展计划(973计划2015CB453000)、国际地球科学计划(IGCP675)项目资助、中国地质调查局地质调查项目(DD20190813) |
| 语种 | 中文 |
| 数据库(集)组成 | 该数据集主要由含铀岩系直罗组地层厚度等值线图、砂体厚度等值线图、顶底板埋深等值线图、含砂率等值线图、放射性异常等值线图等专题成果图集以及含铀岩系直罗组三维地质模型组成 |

## 2　钻孔数据库建库

### 2.1　数据采集

### 2.1.1　收集整理钻孔资料

共收集黄陵地区 9 份煤田地质报告，报告中钻孔总工作量为 820 口，均为扫描

的.pdf格式，工作时间为1975—2004年，工作单位为陕西省煤田地质勘探队。按照2 km×2 km控制网度筛选出354口，包括综合柱状图、工程位置图、岩煤层对比图、勘探线剖面图及各类附表等资料。

### 2.1.2 按入库要求进行数据类型转换

纸质钻孔资料通过扫描方式，生成JPEG、PDF格式电子文件。按数据采集项要求，对钻孔重要属性信息进行数字化。

电子类钻孔资料通过数据类型转换生成JPEG、PDF格式电子文件。按数据采集项要求，对钻孔重要属性信息进行数据采集。

钻孔数据采集内容主要包括项目基础信息、工作区基本信息、钻孔基本信息和属性信息等共计10个数据采集表，其中回溯性煤田钻孔属性采集涉及7个表。

(1) 项目基础信息表 (XMJC)

项目基础信息主要包括项目编号、项目名称、所属行政区划、所属盆地、承担单位名称、组织机构代码、项目负责人、工作目标、工作程度、主要矿种、投入资金总额、项目开始日期、项目结束日期、工程布置图 (扫描图件)、勘探线剖面图 (扫描图件) 和样品分析结果表 (扫描图件) 等。

(2) 工作区基础信息表 (GQJC)

工作区信息主要包括工作区编号、工作区名称、所属项目编号、所属行政区划、所属盆地、工作区面积、主要矿种、矿权数量、磁偏角 (度)、拐点坐标、坐标系、工作开始日期、工作结束日期等内容。

(3) 钻孔基础信息表 (ZKJC)

钻孔基础信息表包括钻孔基本信息和一系列钻孔属性信息表，包括综合柱状信息表、钻孔岩性分层表、地层名称及代号表、地层颜色表、测井曲线配置表、测井曲线数据表、弯曲度测量表等 (图2)。

## 2.2 数据处理过程

### 2.2.1 钻孔数据汇总建库

经数据采集录入为Excel格式的钻孔数据，需通过“砂岩型铀矿钻孔数据采集系统软件”进行数据的正确性、完整性和数据一致性检查，根据软件提示的错误类型对钻孔数据反向检查修改，直至软件提示无误。数据建库主要是将钻孔数据根据关键字段进行挂接并检查，将项目信息、钻孔重要信息、钻孔基础属性信息及各种图件和样品分析报告扫描件等导入钻孔数据采集系统，形成钻孔数据库，且保证数据库运行正常，统计、查询、检索无误。

本钻孔数据库全部为未经处理的原始数据库。

### 2.2.2 钻孔数据库调整更新

值得注意的是，在以往的煤田勘查工作中，不同勘查区的相关工作人员往往各自为政，只对自己勘查区内的地层及煤层信息进行了统一处理校正，在综合利用多个勘查区资料时出现地层划分、地层单位、煤层编号混乱不统一的现象，给区域岩石地层格架的建立和砂体对比造成很大的困难，严重制约了砂岩型铀矿成矿规律等的研究。为此，本次工作通过钻孔数据库与三维可视化软件Gxplorer挂接，通过地层连井剖面、栅状图制作、井—震综合研究等进行区域地层对比，构建等时地层格架，对前人划分不合理之处进行论证修改，并更新至钻孔数据库。

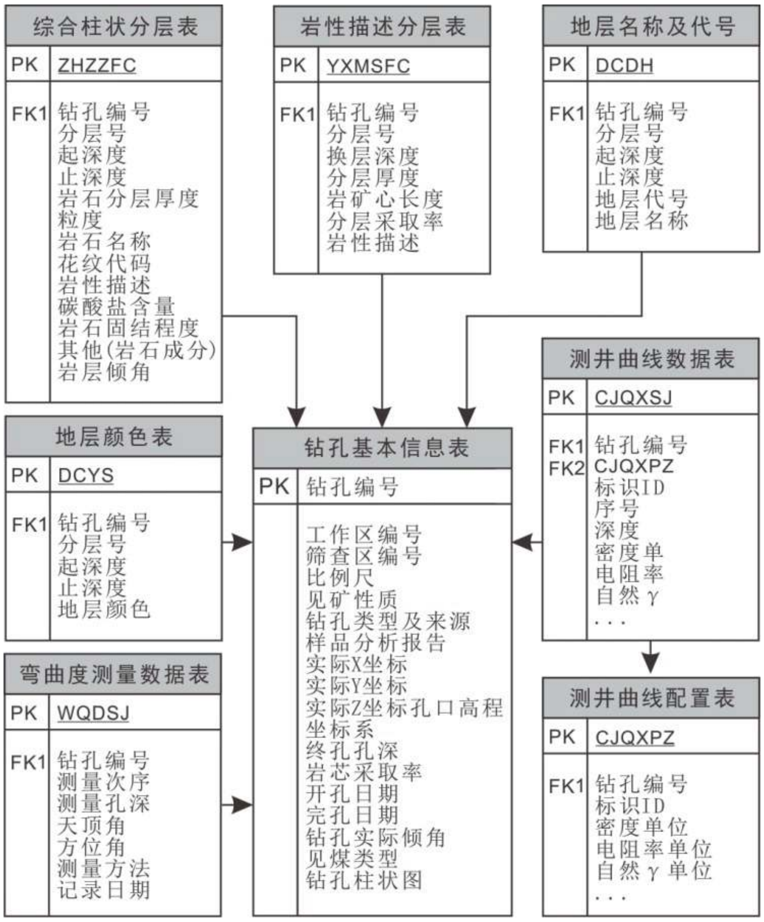

图 2　钻孔属性采集数据表逻辑结构图 (修改自周小希等，2016)

## 3　钻孔数据库应用

### 3.1　含铀岩系专题成果图件编制

含铀岩系专题成果图件编制主要数据源为更新后的钻孔数据库，数据存储格式为 *.mdb，数据结构见图 2，由三维建模软件 Gxplorer 研究平台的平面图数据管理和成图模块来实现平面等值线图的制作，包括含铀岩系顶底板构造等值线图、含铀岩系顶底板埋深图、地层厚度等值线图、砂体厚度等值线图、含砂率等值线图等 (图 3)，提供的含铀岩系专题成果图件格式为 MapGIS(*.wp，*.wl，*.wt) 格式。

### 3.2　三维地质模型构建

研究区内构造作用整体较弱，以舒缓开阔褶皱为主，断裂构造不发育，地层产状缓倾，因此本次三维地质建模可采用自动建模的方法。三维地质结构建模所需数据包括井位数据、井轨迹数据、地层分层数据，软件将钻孔地层信息转换为空间二维离散点数据，再通过插值和拟合算法依次生成构造层面，平滑次数为 1，通过勾选参与建模的层面，再由成图区域确定的地层边界围限进而生成地层实体，再通过“层序建模”模块完成三维地质结构模型构建 (图 4)。此外根据不同的建模目的还需要加载砂体数据 (砂体模型)、相数据 (相模型)、解释结论数据 (矿化体模型) 以及测井曲线数据 (属性模型)。三维地质结构建模是三维地质建模过程中的关键步骤，也是之后建立属性模型、砂体模型、矿化体模型、沉积相模型的基础。结构模型用于描述当前选中地层结构空间位置之

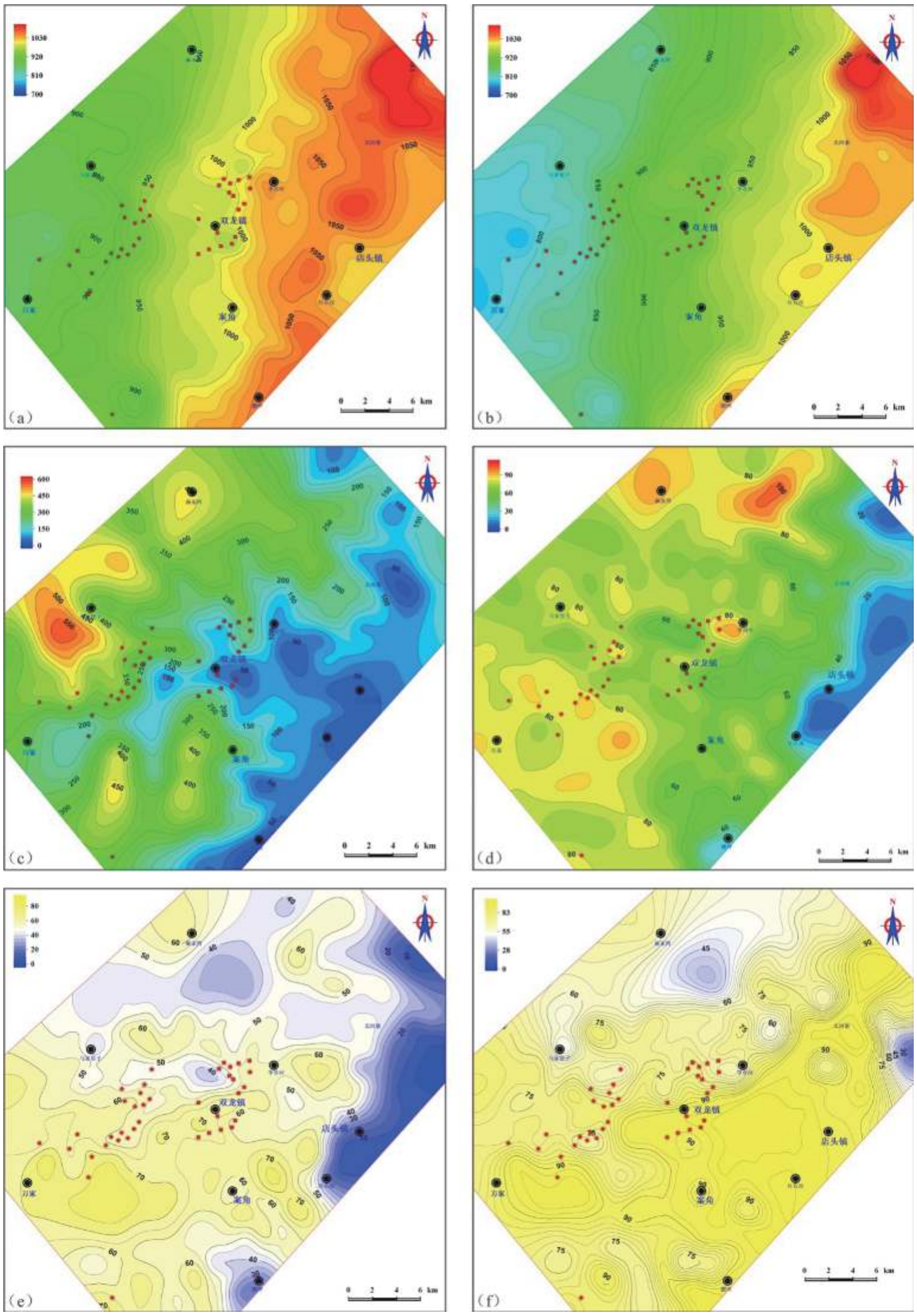

**图 3　鄂尔多斯盆地南缘黄陵地区含煤含铀岩系系列成果图件**

a—直罗组顶板标高等值线图；b—直罗组底板标高等值线图；c—直罗组顶板埋深等值线图；
d—直罗组地层厚度等值线图；e—直罗组砂层厚度等值线图；f—直罗组含砂率等值线图

间的关系，也称为三维地层框架，构造模型的精细程度将影响之后建立实体模型 (如砂体模型) 的准确性。

三维地质结构模型导出为 Eclipse GIRD 模型数据 (*.txt) 格式，本模型可以直观地展示各地层的地貌形态，沉积厚度分布和沉积中心和古隆起剥蚀区，叠加钻孔铀矿化异常信息表明，铀矿化集中发育区域与直罗组古地貌特征和埋深有着密切关联 (图 3c，图 4)，

铀矿验证钻孔 (含矿孔) 集中围绕古隆起与古坳陷过渡斜坡带和埋深骤变边界带展布，与鄂尔多斯盆地东北部成矿地质特征相似 (张天福等，2020)。

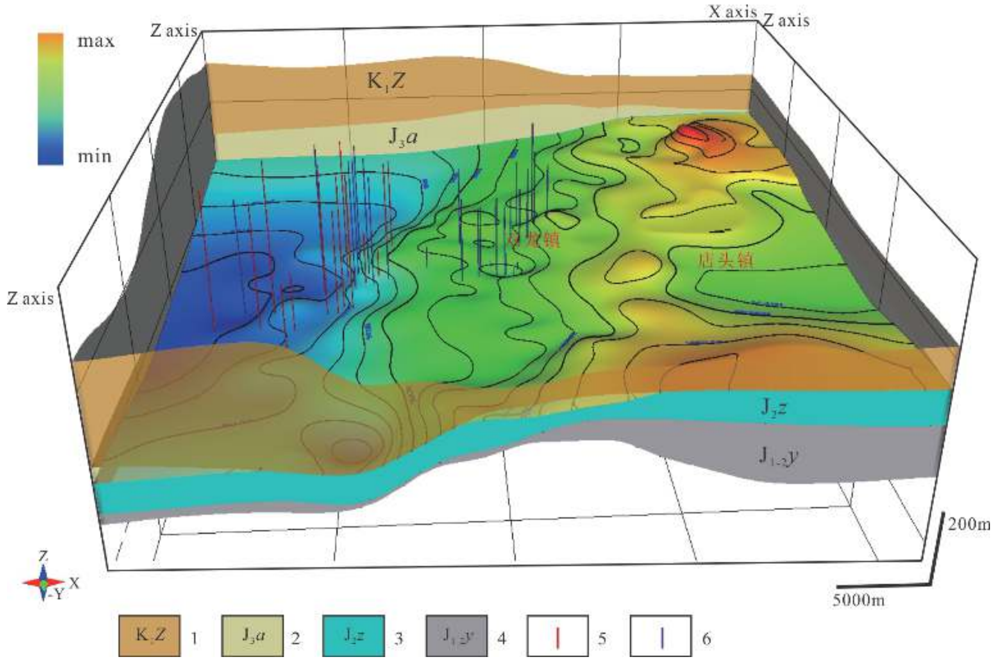

**图 4　鄂尔多斯盆地南缘黄陵地区含煤含铀岩系三维地质结构模型**
**(图面显示为含铀岩系直罗组顶面构造图)**
1—志丹群；2—安定组；3—直罗组；4—延安组；5—铀矿验证钻孔 (含矿孔)；
6—筛选出的潜在砂岩型铀矿 (化) 孔

## 4　数据质量控制

### 4.1　钻孔数据质量控制

钻孔数据采集坚持按照《北方重要盆地砂岩型铀矿钻孔数据库建设技术要求》❷的统一标准，保证数据的真实性、准确性、逻辑一致性、规范性和完整性，对必要的修改变动之处项目组要充分论证，并要有相应的记录和合理性说明。从项目到单位层面逐级做好数据质量控制工作和数据库的审核验收工作，做到自检率达到 100%，互检率达到 100%，项目检查率达到 60%，上级抽查为 15%。在检查中发现的问题，及时找出原因，并认真整改，做到上报数据库错误率低于 0.3%，并针对数据库检查保留相应的检查记录和修改说明。综上，不论在数据采集入库阶段，还是在数据处理阶段都进行了严格的质量控制，确保了数据质量。

### 4.2　专题成果图集及模型质量评估

专题成果图件和三维模型构建所采用的钻孔数据全部来源于本次建库钻孔和已实施的验证钻孔，数据质量可靠。建模区总面积约 1225 $km^2$，参与建模钻孔 375 个，孔距多为 2 km 左右，在双龙地区钻孔相对较密集，孔距约 1 km 左右，整体上钻孔分布较均匀 (图 1a)。同时，通过地层连井剖面、栅状图制作、井-震综合研究等进行区域地层对比，构建等时地层格架，对前人划分不合理之处进行论证修改，并更新至钻孔数据库。更新后的钻孔数据库用于编制系列专题成果图件，保证合理性和可信度。在修改后的地层连井剖面图上开展砂体对比连井、矿化层对比连井，刻画砂体和含矿层的展布形态，

并作为软件模型构建的约束条件参与最终建模。在建模过程中，项目组与软件方协同配合，尝试了多种插值方法和逻辑结构，以保证界面平滑、地质图尖灭合理。三维模型构建完成后，通过剖面对比的方法对模型效果进行了验证，即通过模型裁切形成的连井剖面和利用钻孔绘制的连井剖面进行对比，拟合效果较好，模型总体质量较好。三维模型可以进行剖面、切片、栅状图、数据体 (雕刻体、椅型图、虚拟体等)、沿井轨迹等多种可视化展示方式 (图 5)。

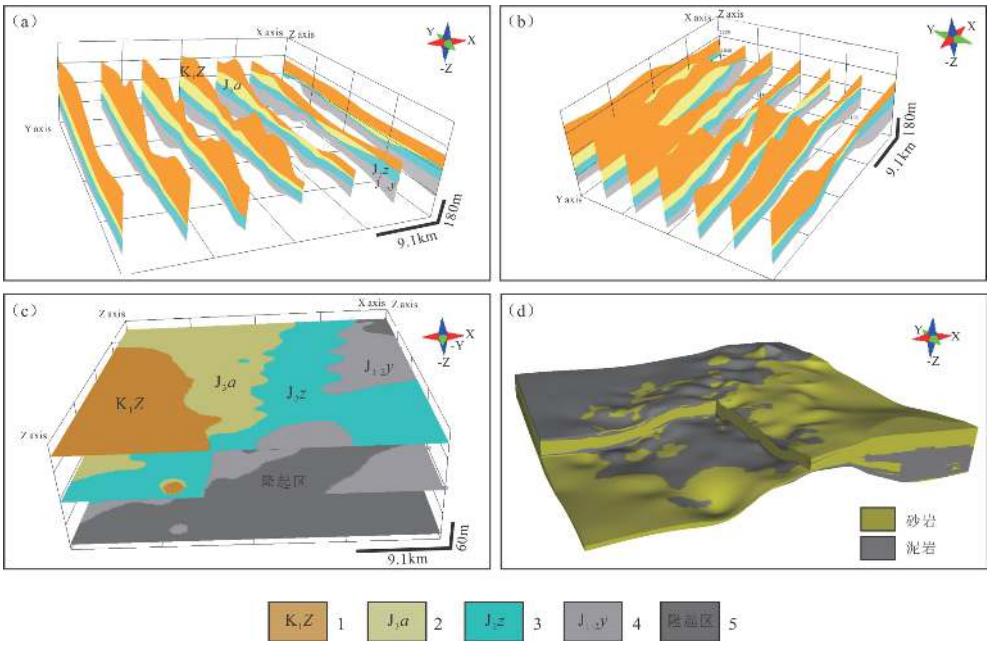

**图 5　三维地质模型可视化方式**

a—三维地质结构模型 XLine 剖面展示；b—三维地质结构模型 YLine 剖面展示；
c—三维地质结构模型水平切片展示；d—三维地质砂体模型椅型图展示

## 5　结论

中国地质调查局在鄂尔多斯盆地南缘黄陵地区部署的砂岩型铀矿钻孔数据库建设工作，集成了研究区 375 个煤田钻孔和验证钻孔，整体上钻孔分布较均匀，能覆盖整个研究区，在钻孔数据采集入库和数据处理阶段都进行了严格的质量控制，确保了数据质量。本专题成果图集是基于钻孔数据集进行编制，直观地展示了含铀岩系直罗组顶底板标高、地层厚度、砂体厚度、含砂率、放射性异常的分布规律，叠加筛查出具放射性异常的煤田孔和已实施验证的工业孔，对研究砂岩型铀矿成矿部位、有利成矿条件和总结成矿规律具有重要的参考和指导意义。三维地质模型直观地再现了含铀岩系的空间展布规律，通过三维模型剖切、沿井轨迹等模型分析和可视化展示功能，可以对工程施工过程进行三维动态模拟，对鄂尔多斯盆地南缘铀矿勘探开发提供了有力的支撑和服务作用。

**致谢：**中国地质调查局天津地质调查中心邓凡工程师、内蒙古自治区地质调查院马海林工程师在论文撰写过程中提供了指导和建议，西安石文软件有限公司刘贤工程师和张章工程师在软件定制化开发和使用过程中提供了帮助，审稿专家和编辑提出了许多宝贵意见，在此一并表示感谢。同时，对陕西省煤田地质勘探队在项目实施过程中提供的数据、资料方面的支持表示感谢。

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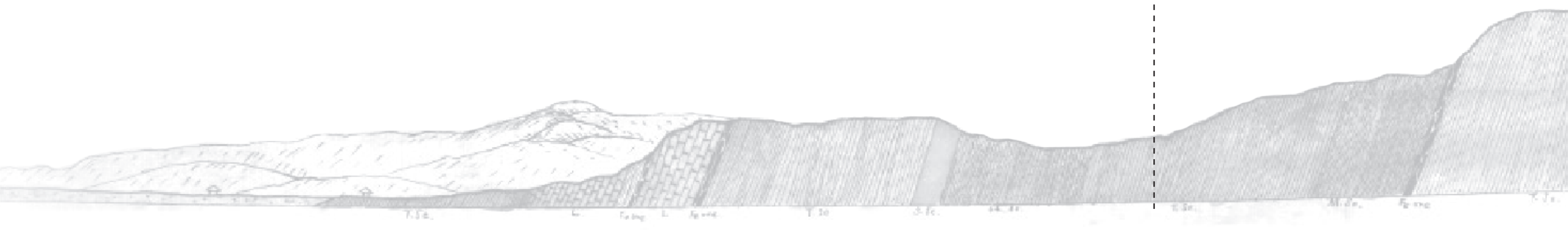

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# Integration of Borehole Data and 3D Geological Modeling of the Huangling Area on the Southern Margin of the Ordos Basin Based on Coal-Uranium Joint Exploration

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**Abstract:** The Huangling area on the southern margin of the Ordos Basin boasts great potential for uranium mineralization. China Geological Survey has organized and implemented 3D geological survey of the uranium-bearing rock series in this area to seek prospecting target areas of in-situ leachable sandstone-hosted uranium deposits. During the survey, the data of the coalfield boreholes were developed and utilized again to determine exploration areas under the guidance of new ideas of joint coal-uranium explorations and joint petroleum-uranium explorations. As a result, the data of 354 coalfield boreholes (49 potential sandstone-hosted uranium ore boreholes) and 21 verified uranium ore boreholes (16 industrial uranium mineralization boreholes) were acquired and a database was created accordingly. Furthermore, a thematic result atlas and a 3D geologic model were established, which mainly constitute the database. The thematic result atlas includes the isoline maps of stratum thickness, sand body thickness, the burial depth of the roof and floor, sand content and radioactive anomalies of the uranium-bearing rock series. Therefore, the database will provide active support and service for the exploration and development of uranium deposits.

**Key words:** sandstone-hosted uranium deposit; integration of borehole data; 3D geologic model; mineral exploration engineering; Huangling area; southern margin of Ordos Basin

**Data service system URL:** http://dcc.cgs.gov.cn

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## 1 Introduction

The Ordos Basin is a large-scale Mesozoic-Cenozoic intracontinental superimposed basin located in the North China Craton (Dong SW et al., 2007). It is one of the large-scale basins in China where multiple types of resources such as oil, gas, coal and uranium coexist (Jin RS et al., 2017; Miao PS et al., 2017a), with up to 2 trillion tons of coal and up to 25 billion tons oil and gas (Sun YM, 2018; Zheng M et al., 2019). Uranium is increasingly demanded as a new and important energy and strategic resource in China, due to the rapid development of the economy and the construction of an ecological civilization. In particular, sandstone-hosted uranium deposits have gradually become one of the major uranium deposits explored in China. Since 2013, the Tianjin Center, China Geological Survey has organized and implemented comprehensive surveys and evaluations of multiple types of deposits such as coal and uranium in major basins of China, aiming to seek prospecting target areas of in-situ leachable sandstone-hosted uranium deposits. Under the guidance of the new ideas of joint coal-uranium explorations and joint petroleum-uranium explorations, the data of the boreholes drilled in coalfields and oilfields were developed and utilized again to research exploration areas, screen and delineate the boreholes with radioactive anomalies and select favorable prospecting target areas and in turn verify them via drilling. Breakthroughs have already been achieved in the aforementioned aspects (Jin RS et al., 2014; Yu RA et al., 2019). Alongside this, great numbers of research results have also been made in sequence stratigraphy (Jin RS and Qin ZA, 2013; Zhang Y et al., 2016; Jin et al., 2018; Zhang TF et al., 2019), biostratigraphy (Sun LX et al., 2017), lithogeochemistry (Liu XX et al., 2016; Zhang TF et al., 2016, 2018) and the metallization and metallogenic rules of uranium deposits (Miao PS et al., 2017b; Chen Y et al., 2017; Feng XX et al., 2017, 2019; Jin et al., 2019).

As the survey site of this study, the Huangling area (Fig. 1a) is located in the southern part of the northern Shaanxi slope of the Ordos Basin (Fig. 1b). It generally features weak tectonism and is mainly covered by a series of gentle and wide folds spreading in a NE-trending, with no fault structures developing. The stratigraphic attitude in this area is gently inclined towards the northwest in general, with a dip less than 5° (Chen HB et al., 2006; Zhang YQ and Liao CZ, 2006). This area is widely covered by loess. The bedrocks are mainly exposed along deep valleys and include an upper Triassic Yanchang Formation ($T_3y$; main petroliferous stratum in the Huangling area), lower-middle Jurassic Yan'an Formation ($J_{1-2}y$; main coal-bearing rock series in the Huangling area), Zhiluo Formation ($J_2z$; main uranium-bearing rock series in the Huangling area), Anding Formation ($J_2a$) of middle Jurassic and Luohe ($K_1l$) and Huanhe Formations ($K_1h$) of lower Cretaceous from bottom to top.

As the most authentic information carrier of underground geological conditions, geological borehole data contain important geological information such as lithology, physical properties, logging curves, testing and analysis and hydrology; thus, providing authentic and credible basic data for geological exploration. Massive data on coalfield boreholes in the Huangling area have been accumulated with the drilling in large-scale regional geological and mineral surveys. However, most of these data are disordered documents and images and thus

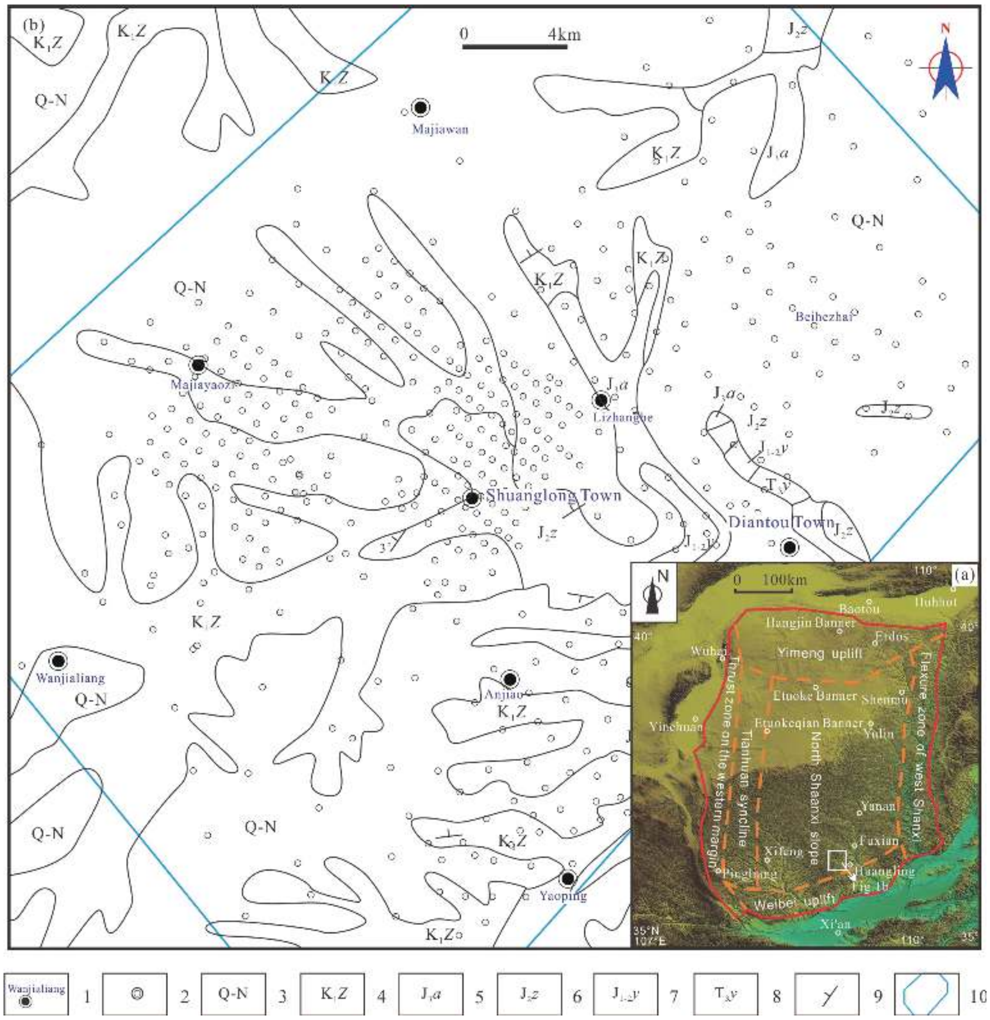

**Fig. 1 Geotectonic location map (a, tectonic zoning is based on Yang JJ and Pei XG, 1996) and borehole distribution map (b, the base map is based on *1 : 500 000 Digital Geological Map Database of Shaanxi Province*①) of the Huangling Area on the southern margin of the Ordos Basin**

1—Geological location and name; 2—Borehole location; 3—Quaternary-tertiary; 4—Zhidan Group; 5—Anding Formation; 6—Zhiluo Formation; 7—Yan'an Formation; 8—Yanchang Formation; 9—Stratigraphic attitude; 10—3D modeling Area

cannot be shared and applied among different industries, making it difficult to realize their true value. The integrated application of relevant geological data has become an urgent need with increasing prospecting of sandstone-hosted uranium deposits (Zhou XX et al., 2016). Furthermore, the secondary development and utilization of these geological data help to effectively reduce the blindness and repetition of geological work, thus greatly improving work efficiency (Wang B et al., 2013). Meanwhile, 3D visual presentation of the geological information derived from borehole data will intuitively exhibit the spatial distribution and mutual relationship of various geological bodies, thus maximizing the intuition and accuracy of geological analysis and facilitating decision-making and automated map drawing of exploration engineering. Previous researchers have made successful attempts in the 3D visual presentation (Xiang ZL et al., 2009; Tian XF et al., 2012; Yu JJ et al., 2015).

This project is supported by a national geological survey project titled *'Survey and*

*Exploration Demonstration of Sandstone-hosted Uranium Deposits in Major Basins of North China'*. During this project, the data of 354 coalfield boreholes of the Huangling area were fully collected for the first time. Then they were collated, scanned, converted into desired data types, input and then integrated into a database in accordance with uniform standards, with the grid density of 2 km × 2 km. After that, boreholes with radioactive anomalies were screened and then verified by drilling into uranium deposits. As a result, a thematic result atlas was prepared, which includes the isoline maps of stratum thickness, sand-body thickness, burial depth of the roof and floor, sand content and radioactive anomalies of the uranium-bearing rock series in the Huangling area. Furthermore, a 3D geological structural model of uranium-bearing rock series and sand body models of the Huangling area were built. All these will provide basic data for the exploration and development of uranium deposits in this area.

The brief metadata table of the dataset of the thematic result atlas and 3D geological modeling of the uranium-hosted rock series (Zhang Y et al., 2020) is shown in Table 1.

## 2 Establishment of Borehole Database

### 2.1 Data Acquisition

### 2.1.1 Collection and Collation of Borehole Data

A total of nine coalfield geological reports of the Huangling area were collected. There

**Table 1 Metadata Table of Database (Dataset)**

| Items | Description |
|---|---|
| Database (dataset) name | Integration of Borehole Data and 3D Geological Modeling of the Huangling Area on the Southern Margin of the Ordos Basin Based on joint Coal-Uranium Explorations |
| Database (dataset) authors | Zhang Yun, Tianjin Center, China Geological Survey<br>Zhang Tianfu, Tianjin Center, China Geological Survey<br>Sun Lixin, Tianjin Center, China Geological Survey |
| Data acquisition time | 2017–2018 |
| Geographic area | 108.7648°–109.1581° E, 35.5163°–35.8410° N; 1225 km$^2$ |
| Data formats | MapGIS (*.wp, *.wl, *.wt) for the atlas, and *.txt for the 3D geologic model dataset |
| Data size | 515 MB |
| Data service system URL | http://dcc.cgs.gov.cn |
| Fund projects | Jointly funded by the National Key R&D Program of China (2018YFC0604200), the National Key Basic Research Program of China (973 Program; 2015CB453000), the International Geoscience Program (IGCP675) and a project initiated by China Geological Survey (DD20190813) |
| Language | Chinese |
| Database (dataset) composition | This dataset mainly consists of a thematic result atlas and a 3D geologic model of Zhiluo Formation as the uranium-bearing rock series. The thematic result atlas includes the isoline maps of stratum thickness, sand-body thickness, burial depth of the roof and floor, sand content and radioactive anomalies. |

were 820 boreholes recorded in the reports, which were drilled by the Coalfield Geological Exploration Team of the Shaanxi Province during 1975—2004. The data of these boreholes are in scanned.pdf files. 354 boreholes were screened according to the grid density of 2 km × 2 km and data of these boreholes include synthetic histograms, project location maps, comparison diagrams of rock strata and coal seams and exploration line profiles.

#### 2.1.2 Data Type Conversion

It is necessary to convert the borehole data into the desired data types in order to input them into the database. The steps are as follows:

Scan paper borehole data to generate.JPEG and.PDF files. Then digitalize important borehole attributes in the data according to the data acquisition items. Next convert electronic borehole data in various formats into.JPEG and.PDF files. After that, acquire important borehole attributes according to the data acquisition items.

The borehole data to be acquired mainly include basic information of projects, survey sites, basic boreholes and attributes. A total of 10 data tables were formed, among which 7 of them were involved in retrospective collection of coalfield borehole attributes.

(1) Data table of basic information of projects (XMJC)

The basic information of a project mainly includes the No., name, the administrative area of the project, the basin where the project is *located*, the name and organization code of the project undertaker, the leader, goals, exploration level, main mineral types, total investment amount, start date, and end date of the project, engineering layout maps (scanned maps), exploration line profiles (scanned diagrams) and forms of sample analysis results (scanned diagrams).

(2) Table of basic information of survey sites (GQJC)

The information about a survey site mainly includes the No., name, project No., and administrative area of the survey site, the basin where the survey site is located, the area, main mineral types, quantity of mineral rights, magnetic declination (degree) of the survey site, coordinates of inflection points, coordinates system and start date and end date of work at the survey site.

(3) Tables of basic information of *boreholes* (ZKJC)

The tables of basic information of boreholes consist of basic information of boreholes and a series of data tables of borehole attributes, including the *Beds based on synthetic histograms*, *Lithological beds of boreholes*, *Names and codes of strata*, *Colors of beds*, *Configuration of logging curves*, *Data from logging curves* and *Bending degree measurement* (Fig. 2).

### 2.2 Data Processing

#### 2.2.1 Borehole Data Collecting into Database

The borehole data collected in an Excel format were checked for accuracy, integrity and consistency using the borehole data collection system software for sandstone-hosted uranium deposits. They were checked retrospectively according to the error types prompted by the software and then modified until the software prompted a “no error” sign. The database was

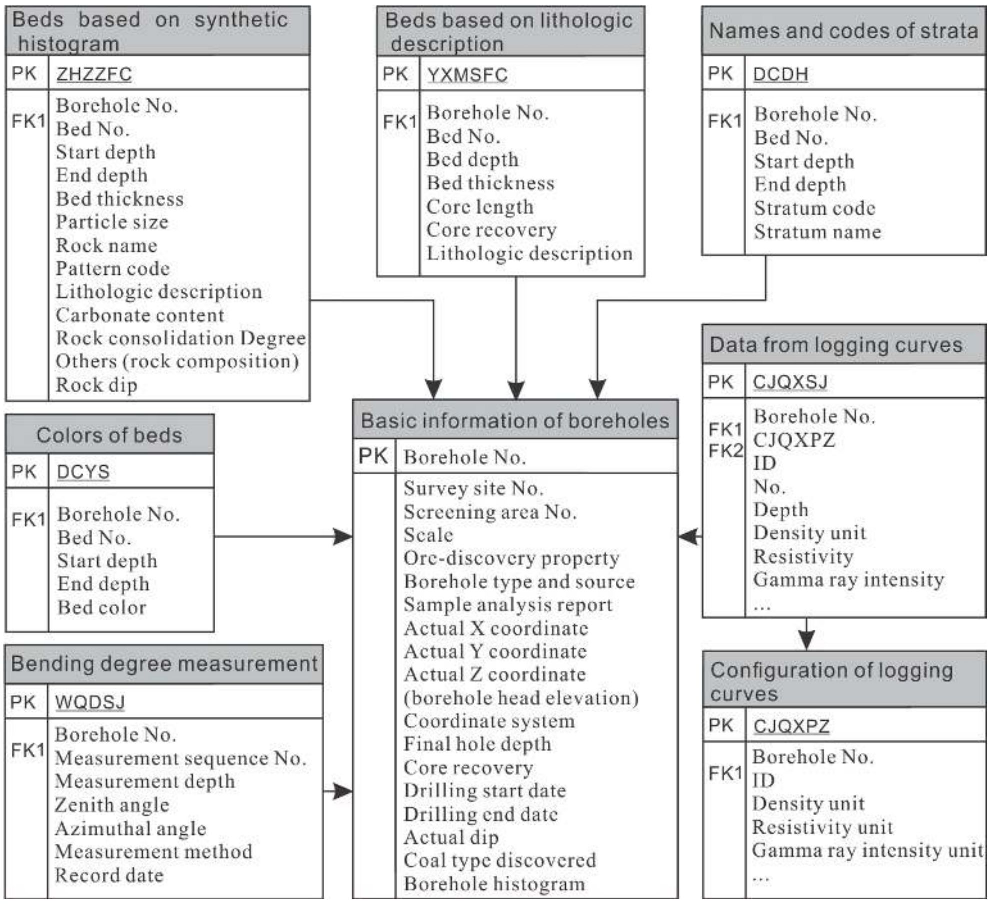

**Fig. 2 Logic structure of the data tables used for acquisition of borehole attributes (modified from Zhou XX et al., 2016)**

mainly established by the following steps: First, link borehole data according to key fields and check. Then import the project information, key information of boreholes, basic attributes of boreholes, various maps and scanned sample analysis reports into the borehole data acquisition system to form the borehole database. Meanwhile, the database was ensured so that it could be operated normally and the statistics, queries and retrievals were made correctly.

All borehole data in the database are original raw data.

### 2.2.2 Adjustment and Updating of the Borehole Database

Careful attention should be paid to the previous coalfield exploration, as the staff working in the different exploration areas tended to carry out the exploration using their own methods and process and correct the information about strata and coal seams solely based on their own exploration areas. Therefore, the comprehensive utilization of the data of multiple exploration areas are often restricted by disordered and non-uniform stratum division, stratigraphic units and coal seam numbers. This can lead to severe difficulties for the establishment of regional petrostratigraphic framework and the comparison of sand bodies, thus seriously restricting the research on metallogenic rules of sandstone-hosted uranium deposits. For this reason, in this project, the borehole database was linked with the 3D visualization software ‘Gxplorer’. Based on this, a regional stratigraphic comparison was conducted through the preparation of profiles and fence diagrams and logging-seismic research and thus, the isochronous stratigraphic framework was established. Once unreasonable strata division was discovered, it was modified based on demonstration and then the borehole database was updated.

## 3 Application of Borehole Database

### 3.1 Preparation of Thematic Result Maps of Uranium-bearing Rock Series

The updated borehole database serves as the data source for the preparation of thematic result maps of the uranium-bearing rock series. It is in the format of *.mdb and its data structure is shown in Fig. 2. The planar isoline maps of the uranium-bearing rock series were prepared using the plan data management and mapping modules of Gxplorer, including the isoline maps of the stratum thickness, sand-body thickness, burial depth of the roof and floor, sand content and radioactive anomalies (Fig. 3). The maps are in the format of MapGIS (*.wp, *.wl, *.wt).

### 3.2 3D Geological Modeling

The Huangling area generally features weak tectonism. It is mainly covered by gentle and wide folds, with no fault structures developing and a stratigraphic attitude gently inclining towards the northwest. Therefore, the 3D geologic modeling of this area can be conducted using automated modeling software. The original data required for 3D geological structural modeling include the data of borehole locations, well trajectories and strata division. Then the software converted the stratum information, revealed by the boreholes, into spatial 2D discrete points, which were then processed by interpolation and fitting algorithms with the smoothing times set to 1. In this way, the tectonic layer surfaces were successively generated. After that, the tectonic layer surfaces to be modeled were selected by ticking the appropriate box in the software. Then they were delineated by stratum boundaries of the areas to be mapped to generate stratum entities. Further to that, a 3D geological structural model was formed by processing the stratum entities in the ‘Sequential Modeling’ module of the software (Fig. 4). In addition, other data may be required for different models, such as sand-body data (for sand-body models), facies data (for facies models), interpretation and conclusion data (for mineralized body models) and logging curve data (for attribute models). The 3D geological structural modeling is a key step in 3D geologic modeling and also serves as the foundation of subsequent modeling of attributes, sand bodies, mineralized bodies and sedimentary facies. It is used to describe the relationships among the spatial locations of the stratigraphic structures currently selected. It is also known as a 3D stratigraphic framework and its level of fineness will affect the accuracy of the physical models that are to be subsequently built (e.g., sand-body models).

The 3D geological structural model is in the format of the Eclipse GIRD model data (*.txt) after being exported. It can intuitively display the landform shapes of various strata, the thickness distribution and centers of sediments and paleo-uplift denudation zones. As indicated by the 3D geological structural model overlapping with the uranium-mineralization anomalies

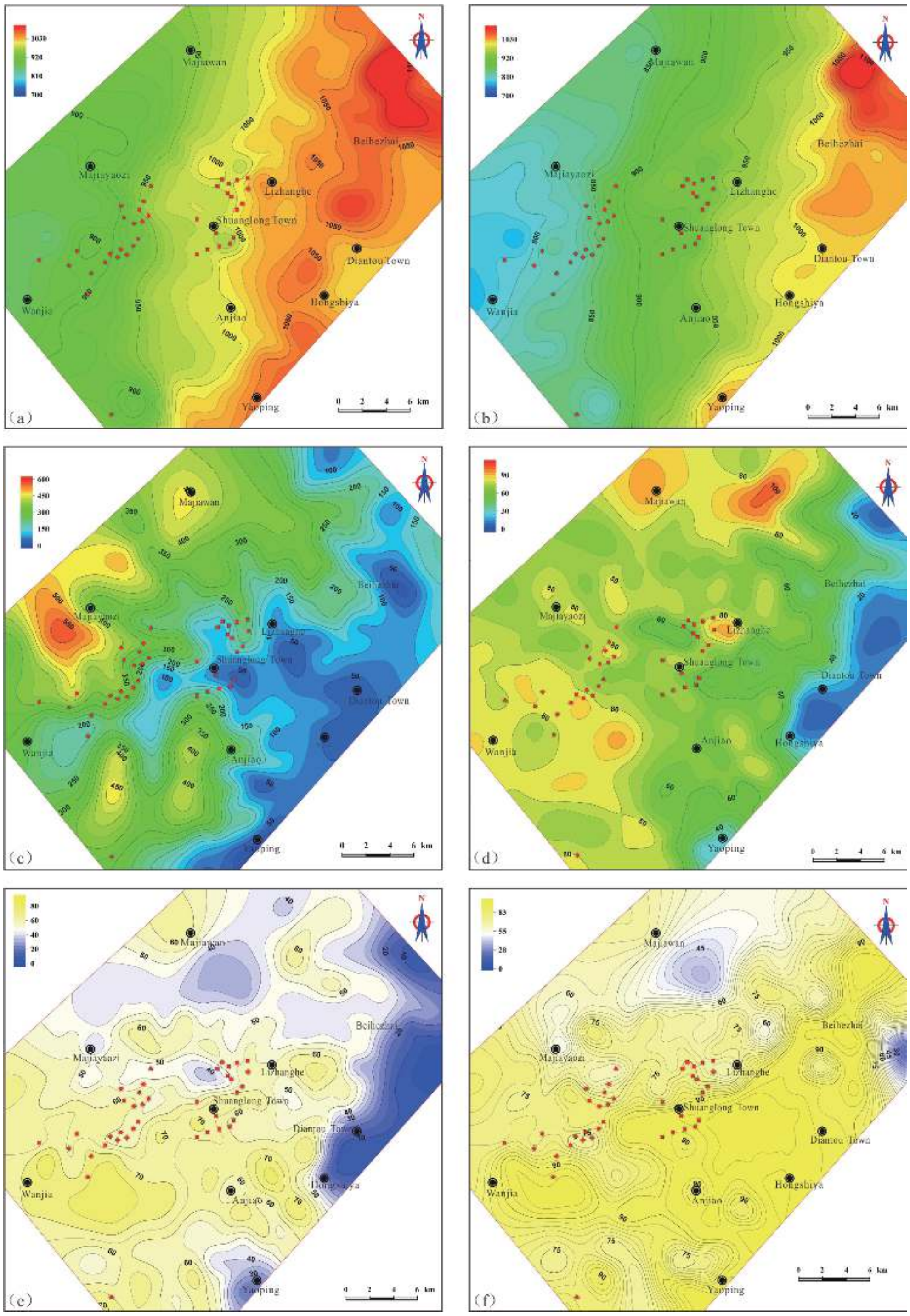

**Fig. 3 Maps of thematic results of the Zhiluo Formation as the coal-bearing and uranium-bearing rock series in the Huangling area on the southern margin of the Ordos Basin**

a–Isoline map of roof elevation; b–Isoline map of floor elevation; c–Isoline map of roof depth; d–Isoline map of stratum thickness; e–Isoline map of sand-layer thickness; f–Isoline map of sand content

revealed by boreholes; the areas where the uranium-mineralization are mainly developed are closely related to the paleo-landform features and the burial depth of Zhiluo Formation (Figs. 3c and 4). The boreholes used to verify uranium deposits (i.e., ore-bearing boreholes) were mainly arranged around the transitional slope zones between paleo-uplifts, paleo-

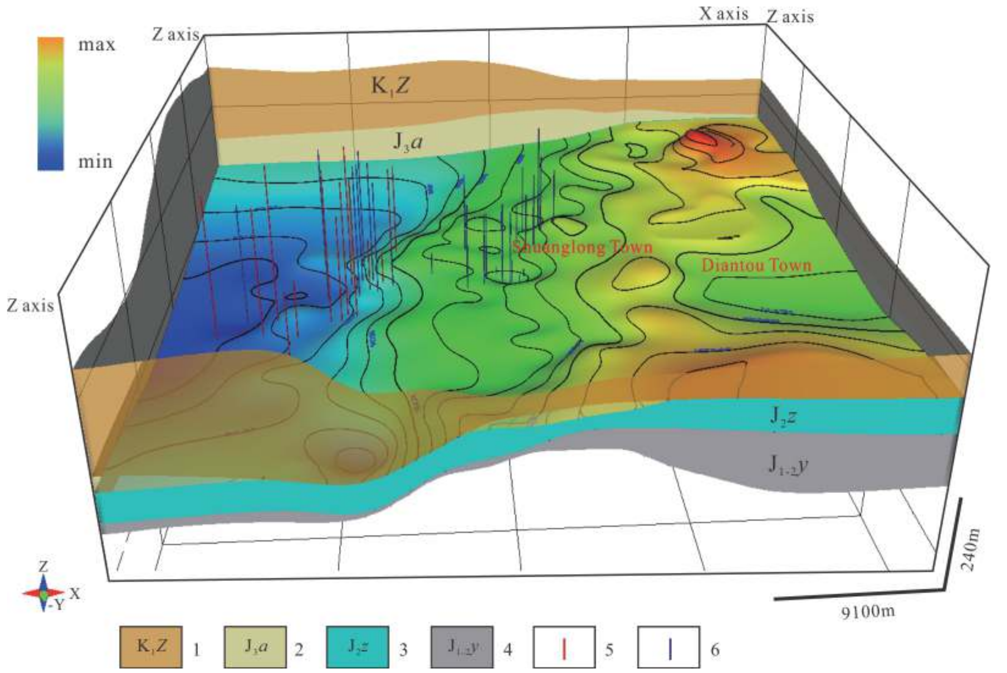

**Fig. 4 3D geological structural model of coal-bearing and uranium-bearing rock series in the Huangling area on the southern margin of the Ordos Basin (the map face showing the tectonic map of the roof of a Zhiluo Formation as the uranium-bearing rock series)**

1–Zhidan Group; 2–Anding Formation; 3–Zhiluo Formation; 4–Yan'an Formation; 5–Boreholes used to verify uranium deposit (ore-bearing boreholes); 6–Potential sandstone-hosted uranium (mineralization) borehole screened out

depression and boundary zones where the burial depth changes sharply. The geological characteristics of mineralization of the uranium-mineralization areas are similar to those in the northeastern region of the Ordos Basin (Zhang TF et al., 2020).

## 4 Data Quality Control

### 4.1 Quality Control of Borehole Data

All of the borehole data were collected in accordance with the uniform standard of the *Technical Requirements for the Building of Borehole Database of Sandstone-hosted Uranium Deposits in Major Basins of North China*❷ to ensure that the data were authentic, accurate, logically consistent, standardized and integral. All necessary modifications and changes were fully demonstrated by the project team, with corresponding records and reasonable explanations provided. The data quality control and the review and acceptance check of the database were sufficiently performed from the project team to the organization responsible for the project. The self-check rate and mutual check rate were both 100%, the rate of inspections conducted by the project team was 60% and the rate of the spot inspection conducted by the organization at a high level was 15%. In case there were any problems arising during the inspection or check, the reasons for such occurrences were rooted out in time and any problems were carefully corrected. In this way, the error rate of the database data submitted was less than 0.3%. Additionally, the corresponding inspection records and modification explanations of the database were kept. To summarise, strict quality control was implemented both at the stage when the data were collected and input into the database and also at the stage of data processing, thus ensuring high quality data.

### 4.2 Quality Assessment of the Thematic Result Atlas and the Geological Structural Model

All of the borehole data used to prepare the thematic result maps and build the 3D geologic structural model are from the data of the boreholes that were used to build the borehole database and to verify uranium deposits. Therefore, they are credible. The modeled region is about 1 225 km$^2$ in total, with 375 boreholes included in the modeling. The borehole interval was generally about 2 km in the region, except for the Shuanglong area, where the interval was about 1km. The boreholes were largely evenly distributed (Fig. 1a). Meanwhile, regional stratigraphic correlation was conducted through the preparation of profiles and fence diagrams and logging-seismic research leading to the establishment of the isochronous stratigraphic framework. Once unreasonable strata division was discovered, it was modified based on demonstration and then the borehole database was updated. The updated borehole database was used to prepare a series of thematic result maps, thus guaranteeing that the maps are rational and credible. Then the distribution form of sand bodies and ore-bearing sandstones was characterized by comparing the sand and mineralized layers on well profiles. In addition, the comparison results were incorporated into the ultimate modeling as the restrictions of the software models. During the modeling, the project team, in collaboration with the software supplier, tried multiple interpolation algorithms and logical structures to ensure smooth interfaces and reasonable thinning-out in the geologic maps. After the 3D geologic structural model was built, the effects of the model were verified through a well profile comparison. This means that well profiles formed by model cutting were compared with those plotted using borehole data. It was concluded that well profiles obtained by these two means were well fitted, and thus the geological structural model features high quality overall. The 3D geologic structural model can be displayed in multiple visualized forms such as sections (profiles), slices, fence diagrams, data bodies (e.g., sculpture bodies, chair-shaped diagrams, and virtual bodies) and well trajectories (Fig. 5). Meanwhile, the software features good compatibility and expansibility and can easily load and export files in multiple formats. In this way, the geological structural model can be shared among different platforms.

## 5 Conclusion

China Geological Survey organized the building of the borehole database of sandstone-hosted uranium deposits in the Huangling area on the southern margin of the Ordos Basin. During this project, 375 coalfield boreholes and the boreholes to verify the uranium deposits were integrated. They were evenly distributed and covered the whole Huangling area. Strict quality control was performed both at the stage when the borehole data were collected and input into the database and at the stage of data processing, thus guaranteeing high data quality. The thematic result atlas was prepared on the basis of borehole database and can intuitively

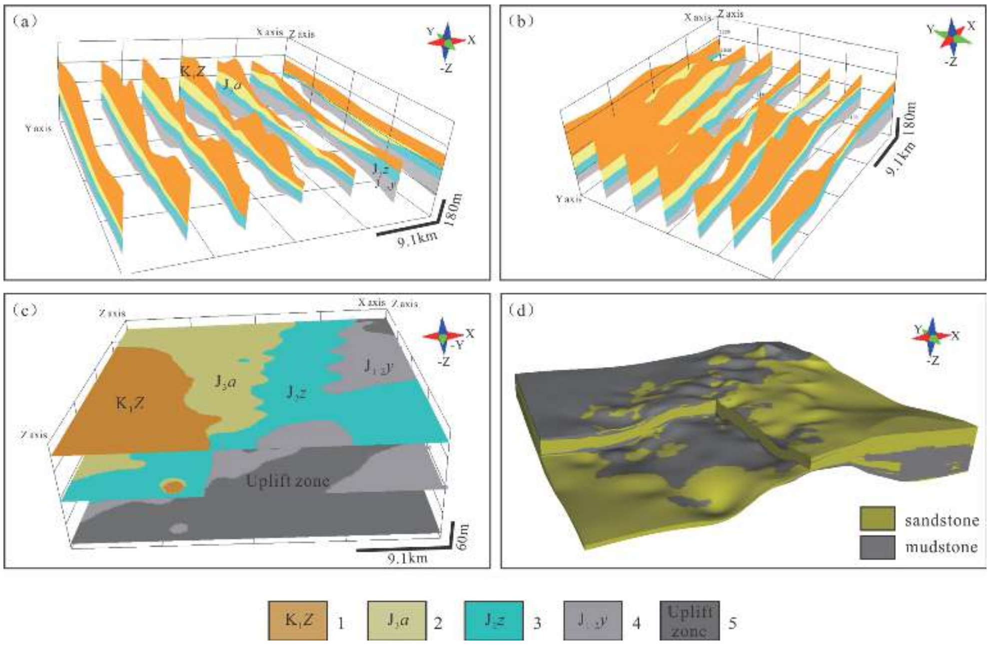

**Fig. 5 Visualized displays of the 3D geologic model**

a–Display of the 3D geological structural model in the form of an XLine section; b–Display of the 3D geological structural model in the form of a YLine section; c–Display of the 3D geological structural model in the form of a horizontal slice; d–Display of the 3D geological structural model in the form of a chair-shaped map

display the distribution rules of the burial depth of the roof and floor, stratum thickness, sand-body thickness, sand content and radioactive anomalies of a Zhiluo Formation as the uranium-bearing rock series in the Huangling area. The boreholes with radioactive anomalies were screened by a superposition method, including coalfield boreholes and the industrial boreholes drilled to verify the uranium deposits. All these will serve as important references and guidance for the research of favorable mineralization conditions and positions of sandstone-hosted uranium deposits, as well as the summary of mineralization rules of the deposits. The 3D geological model was built to intuitively reproduce the spatial distribution rules of the uranium-bearing rock series. It can dynamically simulate the construction process of projects in a 3D manner through visualized representation and model analysis, such as model cutting and well trajectory analysis. Therefore, the 3D geological model will provide strong support and good service for the exploration and development of the uranium deposits on the southern margin of the Ordos Basin.

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**Notes:**

❶ Shaanxi Bureau of Geology and Minerals Exploration. 1999. 1:500 000 Digital Geological Map Database of Shaanxi Province[R]. Xi'an.

❷ Zhou Xiaoxi, Deng Fan. 2018. Technical Requirements for the Building of Borehole Database of Sandstone-Hosted Uranium Deposits in Major Basins of North China[R]. 2018. Tianjin Center, China Geological Survey.

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