В этом году исполнилось 90 лет выдающемуся геологу Китая, человеку, который в течение многих лет являлся ректором Китайского университета наук о Земле в Ухане и Пекине, академику Чжао Пэнда. Благодаря его поддержке более 30 лет назад началось совместное изучение континентальных рифтовых зон учеными Иркутского национального исследовательского технического университета и Китайского университета наук о Земле (г. Ухань). Эти исследования успешно продолжались более 20 лет. Редакционный совет журнала «Науки о Земле и недропользование» сердечно поздравляет академика Чжао Пэнда с юбилейной датой! Мы желаем ему еще долгих лет активной и плодотворной деятельности, здоровья и личного счастья! Ниже журнал публикует статью учеников академика Чжао Пэнда, посвященную его юбилею.

This year marks the 90th anniversary of the outstanding Chinese geologist, long-term rector of the China University of Geosciences in Wuhan and Beijing, Academician Zhao Pengda. Thanks to his support, more than 30 years ago, scientists from the Irkutsk National Research Technical University and the China University of Geosciences (Wuhan) began a joint study of continental rift zones. These studies have been successfully continued for over 20 years. The editorial board of the journal "Earth sciences and subsoil use" cordially congratulates Academician Zhao Pengda on his anniversary! We wish him many more years of active and fruitful work, health, and personal happiness! We wish him many more years of active and fruitful work, health, and personal happiness! Below the journal publishes an article by the students of Academician Zhao Pengda, dedicated to his anniversary.

Original article
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Resource-environment joint forecasting using big data mining and 3D/4D modeling in Luanchuan mining district, China

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Abstract. The Fourth generation industrial age and 5G + intelligent communication in the "Fourth Paradigm of Science" in the 21st century provide a new opportunity for research on the relationship between mining development and environmental protection. This paper is based on the theory of metallogenic geodynamics background, metallogenic process and quantitative evaluation and chooses the Luanchuan district as a case study, using deep-level artificial intelligence mining and three/four-dimensional (3D/4D) multi-disciplinary, multi-parameter and multi-scale modeling technology platform of geoscience big data (including multi-dimensional and multi-scale geological, geophysical, geochemical, hyperspectral and high-resolution remote sensing (multi-temporal) and real-time mining data), carrying out the construction of 3D geological model, metallogenic process model and quantitative exploration model from district to deposit scales and the quantitative prediction and evaluation of the regional Mo polymetallic mineral resources, the aim is to realize the dynamic evaluation of high-precision 3D geological (rock, structure, hydrology, soil, etc.) environment protection and comprehensive development and utilization of mineral resources in digital and wisdom mines, it provides scientific information for the sustainable development of mineral resources and mine environment in the study area. The research results are summarized as follows: (1) The geoscience big data related to mineral resource prediction and evaluation of district include mining data such as

3D geological modeling, geophysics interpretation, geochemistry, and remote sensing modeling, which are combined with GeoCube3.0 software. The optimization of deep targets and comprehensive evaluation of mineral resources in Luanchuan district (500 km^2, 2.5 km deep) have been realized, including 6.5 million tons of Mo, 1.5 million tons of W, and 5 million tons of Pb-Zn-Ag. (2) The 3D geological modeling of geology, mineral deposit, and exploration targeting is related to the mine environment. The data of exploration and mining in the pits of Nannihu – Sandaozhuang – Shangfang deposits and the deep channels of Luotuoshan and Xigou deposits show a poor spatial correlation between the NW-trending porphyry-skarn deposits and the ore bodies. The NE-trending faults are usually tensional or tensional-torsional structures formed in the post-metallogenic period, which is the migration pathway of hydrothermal fluid of the related Pb-Zn deposit. There is a risk of groundwater pollution in the high-altitude Pb-Zn mining zones, such as the Lengshui and Bailugou deposits controlled by NE-trending faults are developed outside of porphyry-skarn types of Mo (W) deposits in the Luanchuan area. (3) Construction of mineral resources and environmental assessment and decision-making in intelligent digital mines: 3D geological model is established in large mines and associated with ancient mining caves, pit, and deep roadway engineering in the mining areas to realize reasonable orientation and sustainable development of mining industry. The hyperspectral database is used to construct three-dimensional useful and harmful element models to realize the association of exploration, mining, and mineral processing mineralogy for the recovery of harmful elements (As, Sb, Hg, etc.). 0.5 m resolution Worldview2 images are used to identify the distribution of Fe in the wastewater and slag slurry of important tailings reservoirs, so as to protect surface runoff and soil pollution.

Keywords: geoscience big data, 3D/4D modeling, quantitative prediction and evaluation, resource and environment, intelligent mine, Luanchuan district

Acknowledgements: this year is Mr. Zhao Pengda's 90th birthday. We write this article to congratulate him! The first author's scientific research and teaching work in recent 20 years is closely related to the higher education postgraduate textbook “Quantitative Geoscience Methods and Applications“ edited by Mr. Zhao (2004). In this textbook, "joint prediction and quantitative evaluation of resources and environment" is considered to be one of the frontier contents of quantitative geoscience research in the 21st century. During the research process, this paper was supported by Professor Clayton Deutsch (University of Alberta, Canada), Professor Cheng Lizhen (University of Quebec, Canada), Professor John Carranza (editor in chief of natural resources research), Professor Khan (University of Houston, USA), Professor Du Yangsong, Associate Professor Cao Yi and postdoctoral Du Jingguo; Thank academician Mo Xuanxue, academician Zhai Yusheng and academician Zhao Pengda for their support; Thank Song Yaowu, Ma Zhenbo, Han Jiangwei, Wang Shiyan, He Yuliang, Guo Bo, Yun Hui, Peng Yi, Du Xin, Liu Guoyin, L. V. Wende, Li Zhongming and Zhang Gubin of Henan Geological Survey Institute for their support. The first author's graduate team has also given strong support in three-dimensional modeling, remote sensing interpretation, resource prediction, and evaluation, and metallogenic process analysis. I would like to express my sincere thanks. The paper was supported by the National Key R&D Program of China (No: 2017YFC0601204).

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Научная статья
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Совместное прогнозирование ресурсов и окружающей среды с использованием интеллектуального анализа больших данных и 3D/4D-моделирования в горнодобывающем районе Луаньчуань, Китай

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Резюме. Промышленная эра четвертого поколения и интеллектуальная связь 5G + в «четвертой парадигме науки» XXI века открывают новые возможности для исследований взаимосвязи между развитием горнодобывающей промышленности и защитой окружающей среды. Эта статья основана на теории металлогенической геодинамики, металлогенических процессах и количественной оценке на примере района Луаньчуань в качестве тематического исследования с использованием глубинного искусственного интеллекта и трехмерного / четырехмерного (3D/4D) междисциплинарного, многопрофильного параметрического и многомасштабного моделирования больших данных, включая многомасштабные геологические, геофизические, геохимические, гиперспектральные и высокоразрешающие данные дистанционного зондирования (разновременные), данные о добыче полезных ископаемых в реальном времени, с выполнением построения трехмерной геологической модели, модели металлогенического процесса и количественной модели разведки от локального района до масштабов месторождения, а также количественного прогнозирования и оценки региональных полиметаллических минеральных ресурсов Mo. Цель исследования заключается в реализации динамической оценки высокоточной трехмерной геологической модели (горные породы, структура, гидрология, почва и т. д.), охраны окружающей среды, комплексного освоения и использования минеральных ресурсов в цифровой среде. Исследование ориентировано на предоставление научной информации по устойчивому развитию минеральных ресурсов и горнодобывающей отрасли в изучаемом регионе. Результаты исследования заключаются в следующем. 1. Большие данные геонаук, связанные с прогнозированием и оценкой минеральных ресурсов в исследуемом районе, включают данные горных работ, такие как трехмерное геологическое моделирование, интерпретация геофизики, геохимия и моделирование дистанционного зондирования, которые объединены с программным обеспечением GeoCube3.0. Проведены оптимизация глубинных данных и комплексная оценка минеральных ресурсов в районе Луаньчуань (500 км^2, глубина – 2,5 км), в том числе 6,5 млн тонн Mo, 1,5 млн т W и 5 млн т Pb-Zn-Ag. 2. Трехмерное геологическое моделирование геологии, месторождений полезных ископаемых и геологоразведочных работ связанно с окружающей средой рудника. Данные разведки и добычи на карьерах месторождений Нанниху – Сандаочжуан – Шанфан и в глубоких руслах месторождений Лутоушань и Сигоу показывают слабую пространственную корреляцию между порфирово-скарновыми месторождениями северо-западного простирания и рудными телами. Разломы северо-восточного простирания обычно представляют собой структуры растяжения или растяжения-кручения, сформированные в пост-металлогенический период и являющиеся путями миграции гидротермального Pb-Zn флюида соответствующего месторождения. Существует риск загрязнения подземных вод в высокогорных зонах добычи Pb-Zn, таких как месторождения Ленгшуй и Байлугоу, контролируемых разломами северо-восточного простирания и разрабатывающихся за пределами месторождений порфирово-скарнового типа Mo (W) в районе Луанчуань. 3. Моделирование минеральных ресурсов, оценка состояния окружающей среды и принятие решений в интеллектуальных цифровых рудниках: трехмерная геологическая модель создается на крупных рудниках и связана с древними горными пещерами, карьерами и глубокими дорожными сооружениями в районах добычи для обеспечения разумной ориентации и устойчивого развития горнодобывающей промышленности. Гиперспектральная база данных используется для построения трехмерных моделей полезных и вредных элементов с целью реализации взаимосвязи минералогии, разведки, добычи и переработки полезных ископаемых для извлечения вредных элементов (As, Sb, Hg и т. д.). Используются изображения Worldview2 с разрешением 0,5 м для определения распределения Fe в сточных водах и шламах важных хвостохранилищ, позволяющие защитить поверхностный сток и загрязнение почвы.

Ключевые слова: большие данные геонаук, 3D/4D-моделирование, количественный прогноз и оценка, ресурсы и окружающая среда, интеллектуальная добыча, район Луаньчуань

Благодарности: в этом году господину Чжао Пэнда исполняется 90 лет, и эта статья написана, чтобы поздравить его с юбилеем. Первые научные исследования и преподавательская деятельность автора за последние 20 лет были тесно связаны с учебником для аспирантов высших учебных заведений «Количественные методы геолого-геофизических наук и их применения» под редакцией господина Чжао (2004). В этом учебнике «совместное прогнозирование и количественная оценка ресурсов и окружающей среды» рассматриваются как одни из важнейших элементов содержания количественных геолого-геофизических исследований в XXI веке. Исследовательский процесс в рамках написания данной статьи поддержали профессор Клейтон Дойч (Университет Альберты, Канада), профессор Чэн Личжэнь (Университет Квебека, Канада), профессор Джон Карранза (главный редактор журнала Natural Resources Research), профессор Хан (Университет Хьюстона, США), профессор Ду Янсун, доцент Цао И и докторант Ду Цзинго. Также благодарю академика Мо Сюаньсюе, академика Чжай Юйшэн и академика Чжао Пэнда за поддержку. Благодарю Сун Яоу, Ма Чжэньбо, Хань Цзянвэй, Ван Шиянь, Хэ Юйлян, Го Бо, Юнь Хуй, Пэн И, Ду Синь, Лю Гоинь, Л. В. Венде, Ли Чжунмин и Чжан Губинь из Хэнаньского института геологической службы за их поддержку. Команда выпускников первого автора также оказала значительную помощь и поддержку в трехмерном моделировании, интерпретации данных дистанционного зондирования, прогнозировании и оценке ресурсов, а также в анализе металлогенических процессов. Хочу им выразить свою искреннюю благодарность. Работа была выполнена при поддержке Национальной программы ключевых исследований и разработок Китая (№ 2017YFC0601204).

Для цитирования: Ван Гунвэнь, Чжан Шоутин, Янь Чанхай, Пан Чжэньшань, Ван Хунвэй, Фэн Чжанькуй [и др.]. Совместное прогнозирование ресурсов и окружающей среды с использованием интеллектуального анализа больших данных и 3D/4D-моделирования в горнодобывающем районе Луаньчуань, Китай // Науки о Земле и недропользование. 2021. Т. 44. № 3. С. 219–242. https://doi.org/10.21285/2686-9993-2021-44-3-219-242.

Introduction

In the 21st century, the intelligence and intelligent manufacturing of the fourth generation industry age promoted the rapid development of new engineering innovation, 5G + communication, cloud computing, and other real-time intelligent decision-making, provided scientific and technological support for the Fourth Paradigm of Science (Data-Intensive Scientific Discovery)[1], and also provided a new opportunity for comprehensive research on mining development and environmental protection. The geoscience system research of lithosphere, biosphere, hydrosphere, and atmosphere becomes the core content and frontier field.

Zhao put forward that the exploration and development of mineral resources in the 21st century must achieve the unity of social, economic, and environmental benefits [1], which require the joint evaluation of mineral resources and environment, and the combination of mineral mapping and mineral exploration. Since 2011, 117 key districts in 16 regional metallogenic belts in China were implemented to deep (less than 1000 m) mineral exploration based on the 1:50000 geological mapping. A series of metallogenic theories and technologies were constructed, for example, Ye et al. [2] built theory and method of prospecting prediction in mineral exploration zone, and the ore-forming dynamic background, process, and quantitative evaluation of large and super-large deposits [3–5]. The 13th five-year national key research and development plan "deep resources exploration and exploitation" has promoted the deep (less than 3000 m) resource prospecting, prediction, and evaluation of key districts in China [6–15].

Most European countries and the United States have established the "industry and university" research alliance of geosciences using the interdisciplinary 3D/4D modeling. The alliance proposed 3D/4D modeling and artificial intelligence technology as the basis of mineral exploration and extraction of geoscience information in recent years [16–20]. For example, OneGeology team developed the 3D geoscience modeling using artificial intelligence and big data with Loop 3D methodology (RFG, 2018). Australia developed the GlassEarth (1998), Uncover (2006) and BigEarth (2018) plans to explore 1000 m, 3500 m and 10000 m potential mineral deposits in deep, respectively, and the Loop3D technology is developed as the future 3D/4D geoscience modeling platform. The United States Geology Survey made 2013-2023 deep exploration plan to construct 3D/4D geological modeling for the resources and environment protection in USA. Mira Geoscience international mining company developed 4D wisdom management platform with the combination of 3D exploration and big data for the real-time-mining. Geological Cloud 3.0 developed by China Geology Survey can build real-time and multi-scale (region, district, camp, deposit) geological mapping and the 3D borehole, orebody and mining modeling. Based on the metallogenic system and mineral system theories, 3D/4D modeling has been used to construct an exploration model of mineral deposits [13, 14].

The aim of this study is to realize the dynamic evaluation of high-precision 3D geological (rock, structure, stratum, and orebody) modeling and environment protection, and enhance the comprehensive development and utilization of mineral resources in digital and intelligent mines using geoscience big data, geodynamic background, metallogenic process and quantitative evaluation of large and super-large deposits [21–30]. The result provides a scientific basis for the sustainable development of mineral resources and mine environment in the study area.

Geological setting and deposit features

The Luanchuan district (25 km × 20 km × 2.5 km (depth) in 3D space) is located in the northeastern part of the Qinling Orogen Belt. The Qinling Orogenic Belt extends for more than 2,200 km in NW-trending distribution and separates the North China Craton from the South China Craton (Fig. 1). The main strata exposed in the study area include the Neoproterozoic Luanchuan Group and the Taowan Group, the Mesoproterozoic Guandaokou Group, and the Neoproterozoic Kuanping Group from the north to

[1] Gray J., Szalay A. *A transformed scientific method: technical report*. Mountain View: National Research Council – Computer Science and Telecommunications Board; 2007.

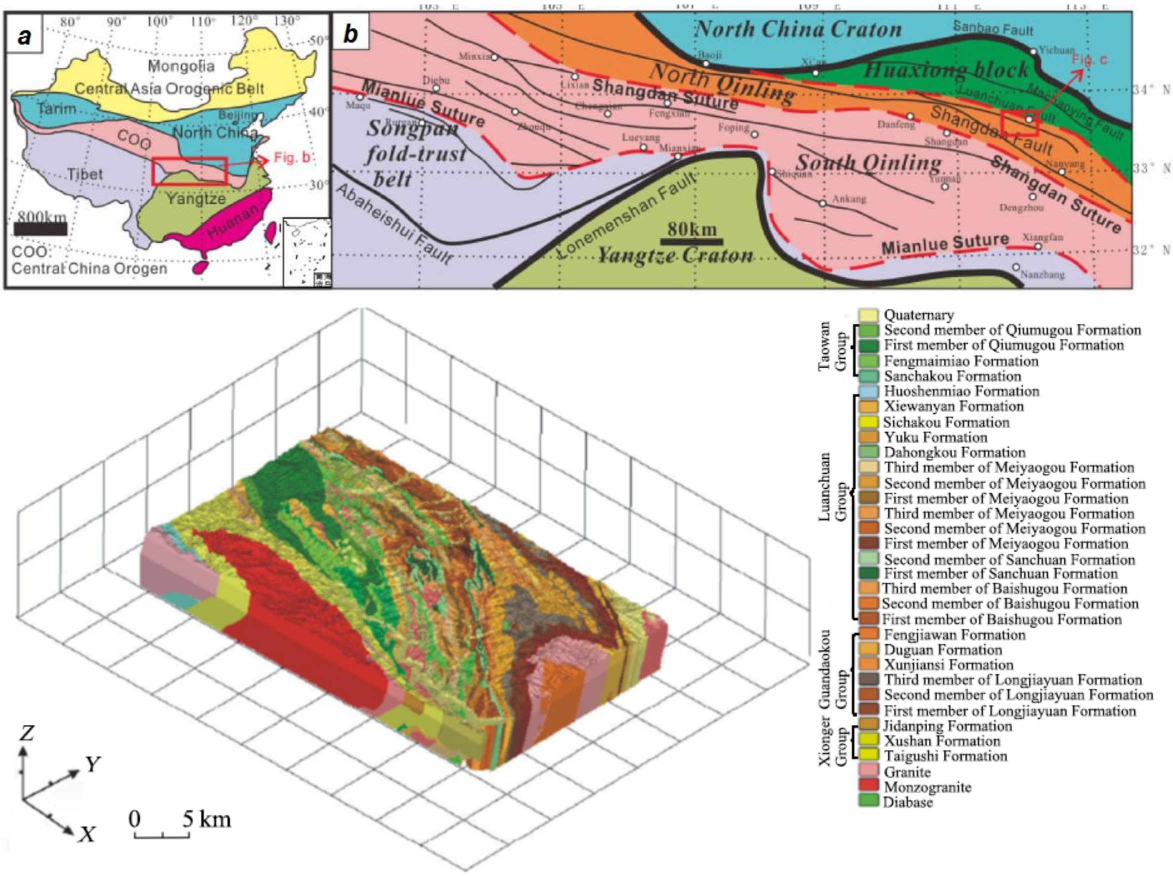

Fig. 1. 3D geological model of the Luanchuan district
Рис. 1. Геологическая 3D-модель района Луаньчуань

south [21, 22]. The Luanchuan Group as the main hosting stratum for ore body has a thickness of ~3100 m and consists of carbonate-clastic rocks formed in a shallow-marine environment, of which ~2,050 m (Sanchuan (Pt3S), Nannihu (Pt3N), Meiyaogou (Pt3M) and Yuku (Pt3Y) Formations from the bottom upwards) is associated with Mo and Pb-Zn-Ag-Au mineralization (Fig. 2). The regional structures in the Luanchuan district define a network of NW- and NE-trending faults. The Luanchuan Group is in a faulted contact with or unconformably overlain by the Taowan Group. The Luanchuan and Zhuyuangou faults constitute the boundaries of the tectonic framework of the Mo deposits. The intersections of the NE- and NW- trending faults control the intrusions and spatial distribution of small acidic-intermediate plutons and are the structures controlling the vein-type Pb-Zn-Ag deposits. During the Jurassic, small-scale granitic stocks, dikes, and breccia pipes were formed, whereas, during the Cretaceous, large-scale batholiths were developed [6]. The plutonic rocks in the Luanchuan district consist of Late Proterozoic syenite and Jurassic granite. The latter one consists of either massive / extensive granite batholith or stocks / dikes of granite porphyry, and they are known to be associated with Mo-W-Pb-Zn mineralization in the study area.

There are five large Mo polymetallic deposits and more than 20 small / medium Pb-Zn deposits in the study area (Table), and all the large Mo polymetallic deposits are hosted by the Luanchuan Group. The molybdenite Re-Os and sphalerite Rb-Sr isotopic dating showed Mo and Pb-Zn mineralization occurred at ~145 Ma and ~139 Ma, respectively [6, 20]. Most of the hydrothermal vein-type Pb-Zn deposits in the district have a close Spatio-temporal relationship with the porphyry-skarn deposits. All Jurassic granitic stocks, including those host the Mo-W mineralization at Nannihu, Shangfanggou, Shibaogou, and the Huangbeiling, are shallow-level and consist of granodiorite, monzogranite, and granite porphyry stocks which are correlatedto one batholith at the depth [27]. The magmatic evolution from granodiorite to monzogranite and to granite porphyry reflects an increase in silica and alkalis,

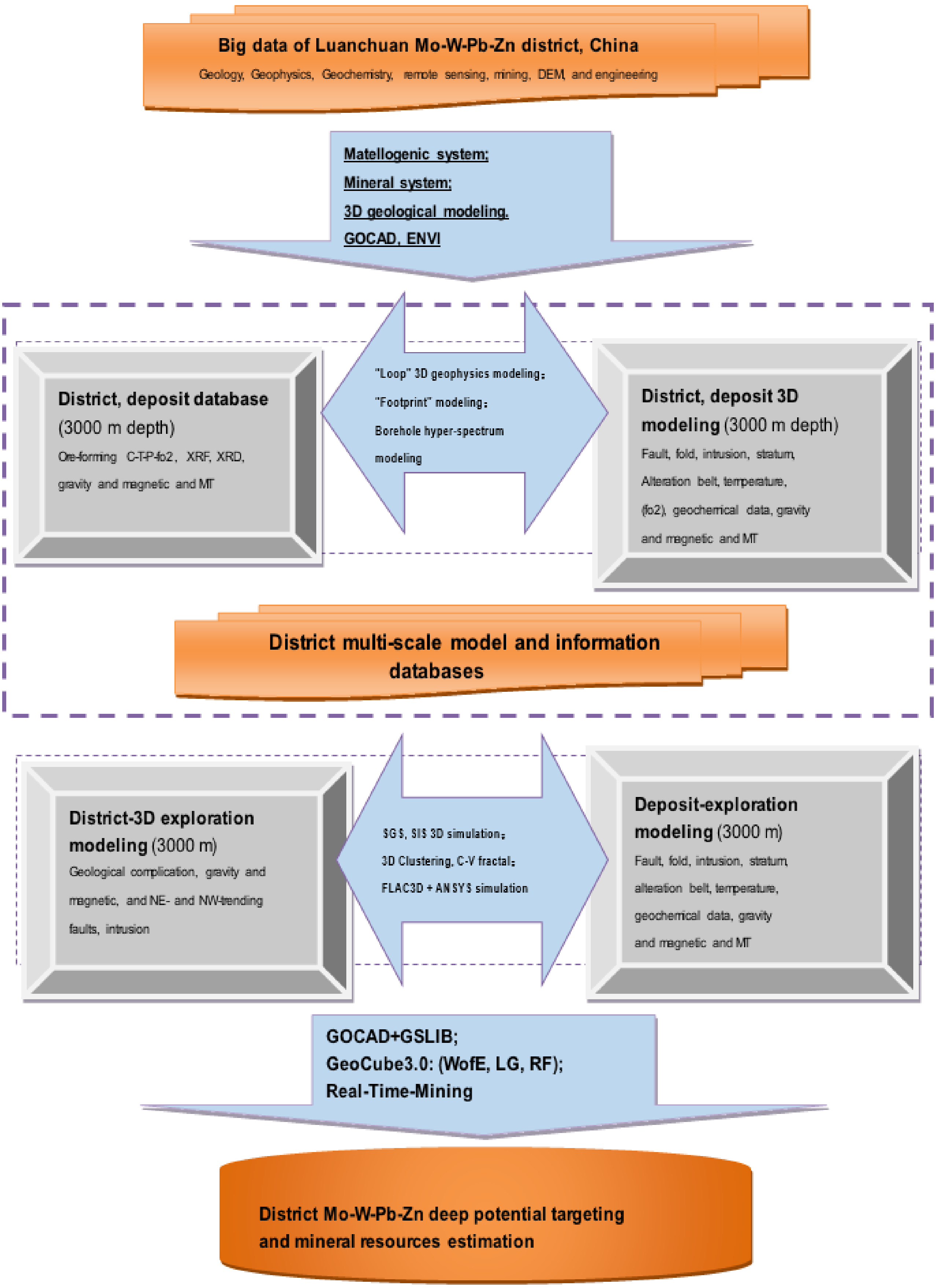

Fig. 2. The workflow of 3D targeting and mineral resources calculation in the study area
Рис. 2. Рабочий процесс 3D-целеполагания и подсчета запасов полезных ископаемых на исследуемой территории

Optimization of main targets of Mo and Pb-Zn mining zones in Luanchuan district based on GeoCube software integration
Оптимизация основных целей зон добычи Mo и Pb-Zn в районе Луаньчуань на основе интеграции программного обеспечения GeoCube

Target	Number	Target	Location (X, Y, Z)	Target delineation	Minerals	Mineral resources (reserve) 10^4 t
A	A1	Daping	553400,3748700,1040	The surrounding area of Daping rock mass is a shallow concealed section, and the ore is predicted to be found 100 m below the surface. The exposed rock mass and Mo polymetallic ore vein on the surface have strong alteration, developed fault structures and folds, and obvious geophysical anomalies. Estimation domain: porphyry skarn Mo and hydrothermal vein Pb Zn deposits	Pb-Zn, Mo	Mo 30 Pb-Zn 120
	A2	Niandaogou	549100,3751300,920	The northeast of shibaogou rock mass is a shallow concealed section. It is predicted that ore can be found 200 m below the surface. There are concealed rock mass (lying on the north side of shibaogou rock mass). The NE trending structure has significant ore control and geophysical anomaly. Estimation domain: hydrothermal vein Pb Zn deposit	Pb-Zn, Mo	Mo 30 Pb-Zn 110
	A3	Zhazigou1	547500,3750400,1100	The northwest of shibaogou rock mass is a shallow concealed section. It is predicted that ore can be found 200m below the surface, and there are concealed rock mass (shibaogou rock mass is NE trending laterally). The NE trending structure controls the ore significantly, and the geophysical anomaly is obvious. Estimation domain: hydrothermal vein Pb Zn deposit	Pb-Zn, Mo	Mo 40 Pb-Zn 120
	A4	Danangou	542200,3753000,1340	The southwest of the ore type Shangfang is a concealed ore section. The predicted target area is as deep as 500 m above sea level, with concealed rock mass. The NE trending structure controls the ore significantly, and the geophysical anomaly is obvious. Estimation domain: porphyry skarn Mo and hydrothermal vein Pb Zn deposits	Pb-Zn, Mo	Mo 10 Pb-Zn 100
	A5	Lengshui West	541300,3758300,920	There is a concealed ore section in the west of Lengshui. The predicted target area is as deep as 600 m above sea level, with concealed rock mass, significant ne structural ore control and obvious geophysical anomaly. Estimation domain: porphyry skarn Mo and hydrothermal vein Pb Zn deposits	Pb-Zn, Mo	Mo 10 Pb-Zn 100

	A6	Huoshenmiao East	532400,375750,560	The east of huoshenmiao is a concealed ore section. The predicted target area is below 300 m above sea level, with concealed medium acid rock mass and basic rock mass distributed, with obvious geophysical anomaly. Estimation domain: porphyry skarn Mo and hydrothermal vein Pb Zn deposits	Pb-Zn, Mo	Mo 30 Pb-Zn 110
	A7	Yuku North	544900,3749400,860	The north of Dongyu reservoir is a shallow concealed section. It is predicted that ore can be found 200 m below the surface of the target area, with concealed medium acid rock mass and basic rock mass distributed, with obvious geophysical anomaly. Estimation domain: porphyry skarn Mo and hydrothermal vein Pb Zn deposits	Pb-Zn, Mo	Mo 40 Pb-Zn 100
B	B1	Huangbeiling West	540990,3750800,1250	The West and northwest of Huangbeiling are Pb Zn prediction prospecting targets, and there is mo prospect in the northwest. Concealed rock bodies are distributed, and geophysical anomalies are obvious. Estimation domain: porphyry skarn Mo ore and hydrothermal vein Pb Zn ore	Pb-Zn, Mo	Mo 40 Pb-Zn 80
	B2	Hongdonggou Eastsouth	539800,3747400,1100	The southeast of hongdonggou is a Pb Zn prospecting target area. The characteristics of structural ore control are obvious; Small acid rock bodies are distributed in taowan group, with obvious geophysical anomalies. Estimation domain: hydrothermal vein Pb Zn deposit	Pb-Zn	Pb-Zn 70
	B3	Baishadong EastSouth	554500,3755300,980	The southeast of baishadong is a Pb Zn prospecting target area. NW and NE trending structures have significant ore control characteristics; The strata of the exposed pipeline mouth group may have Yanshanian rock mass or dyke in the deep, and the geophysical anomaly is obvious. Estimation domain: hydrothermal vein Pb Zn deposit	Pb-Zn	Pb-Zn 60

accompanied by increasing Mo-W and decreasing mafic components. The outcropping Nannihu granite porphyry stock covers about 0.12 km^2 at the surface, with porphyritic monzogranite at shallow levels. The types of hydrothermal alteration at the Nannihu deposit include: (1) potassic alteration, with biotite and feldspar as predominant hydrothermal minerals; (2) silicification is widespread in the porphyry and wall rocks and particularly associated with the quartz-(sulfide) stockworks or veinlets; (3) sericitization is formed by replacement of feldspar and biotite to sericite, with disseminated pyrite and quartz-sericite veinlets; and (4) carbonation is associated with replacement of mafic minerals by carbonates. However, it is magnesian skarn in Shangfang Mo-W-Fe deposit with the mining engineering discovery in recent years, the early stage is associated with porphyry mineralization, and the serpentine, talc and phlogopite are the main secondary which affected the metallurgy process especially the Mo rate of recovery in digital mines. Therefore, the complex skarn mineral system needs high-precious 3D multiple minerals modeling to support the digital and intelligence mines in the study area.

Methodology

The methodology of geoscience big data in the study area is related to mineral resource prediction and evaluation [31–52], including 3D geological modeling, forward calculation, and constrained inversion of the 3D geophysics interpretation using the geological model and metallogenic model with Loop 3D methods, geochemistry, and remote sensing interpretation, etc., combined with self-developed GeoCube3.0 software with seven integration methods [6, 14].

The procedures for 3D modeling and integration of spatial features for generation of exploration targets involved four stages: (1) 3D geological modeling for understanding the district-scale ore-forming geological bodies; (2) 3D modeling of large Mo-W-Pb-Zn deposits for understanding metallogenic model; (3) 3D modeling and extraction of exploration criteria representing potential targeting using big data of geoscience datasets, such as (a) gravity and magnetic features, (b) Jurassic mineralized granite porphyry stocks, (c) NW- and NE- trending ore-controlling faults and (d) Luanchuan Group ore-controlling strata; and finally (4) integration of features representing exploration criteria using boost weights-of-evidence (boost WofE).

Geosciences Datasets. 3D geological models of the Luanchuan district (25.0 km × 20.0 km × 2.5 km) were constructed from geoscience datasets with a uniform geological coding system (Fig. 1). The geoscience data comprise nine geological cross-sections, a 1:10,000 scale geological and topographic map, 1:25000 gravity and magnetic interpretation, and AMT and CSAMT sections [21, 23, 24], 1500 boreholes (the maximum depth is 1832 m) with 36,000 geochemical data and 937 hand specimens at the subsurface (channel), and 9,870 surface geophysical survey points (gravity, magnetic, and topographic).

The 3D study area measures 25 km in the E-W direction and 20 km in the N-S direction, and the elevation range of the borehole and geophysical datasets varies from 1500 m to -1000 m. The Micromine, ArcGIS, MapGIS, AutoCAD, Aess, GOCAD, and self-development GeoCube2.0 were used to implement the geoscience datasets. The methodology was delineated by Figs. 3 and 4.

3D modeling of deposits and geological model. The Nannihu, Sandaozhuang, and Shangfang deposits are the largest porphyry-skarn Mo deposits in the Luanchuan district. These deposits have been explored to depths of more than 900 m. The Mo reserves for each of them are about 700,000 t (the depth is 1500 m). Therefore, 3D modeling of Mo deposits in the district is very important for the analysis of the spatial correlations with geological and metallogenic features, e. g., optimum 3D space distance of spatial correlation between Jurassic granite porphyry stocks and large Mo deposits.

The 3D explicit modeling is used to construct the geological model with borehole, channel, and cross-section datasets, and 3D explicit modeling is used to construct the alteration and grade models with GOCAD 18.0 software (Fig. 5).

Integration of exploration criteria and potential targeting. The integration of exploration criteria in the study area is implemented by combining the exploration model and feasible exploration criteria in 3D space (the depth is 3000 m).

The boost WofE method was used to integrate exploration criteria (metallogenic information of metallogenic model) for identification of potential Mo polymetallic targets with GeoCube 2.0 software [23]. The uncertainty of deep potential targets was analyzed by gravity and magnetic and MT image joint modeling.

Uncertainty analysis of 3D geological modeling and targeting. The 3D geological modeling and mapping have several uncertainties including the multiple scale geological boundary and geometry in 3D space. In this paper, the following uncertainty analyses were delineated:

(1) The Flac3D simulation was used to construct the uncertainty of ore-bearing and ore-controlling geological bodies including the porphyry stocks and NW-trending faults (Fig. 6*, a*).

(2) The experimental metallogenic dynamic laboratory was implemented to quantify the vertical and horizontal parameters (dip, width, strike, etc.) of the thrust nappe structure in the Luanchuan district (Fig. 6*, b*).

(3) The potential targeting was interpreted by the key exploration criteria using metallogenic

and exploration models and mineral systems. The A-type targets generally include known Mo-W deposits and several Pb-Zn deposits with almost exploration criteria; the B-type targets generally include few Pb-Zn deposits with main exploration criteria. The deep targets are supported by the multiple parameters of geophysics and concealed porphyry stocks and near NW- trending faults. Therefore, the geological and metallogenic genesis exploration criteria in this paper are associated with the mineral systems of Mo-W-Pb-Zn deposits in the study area.

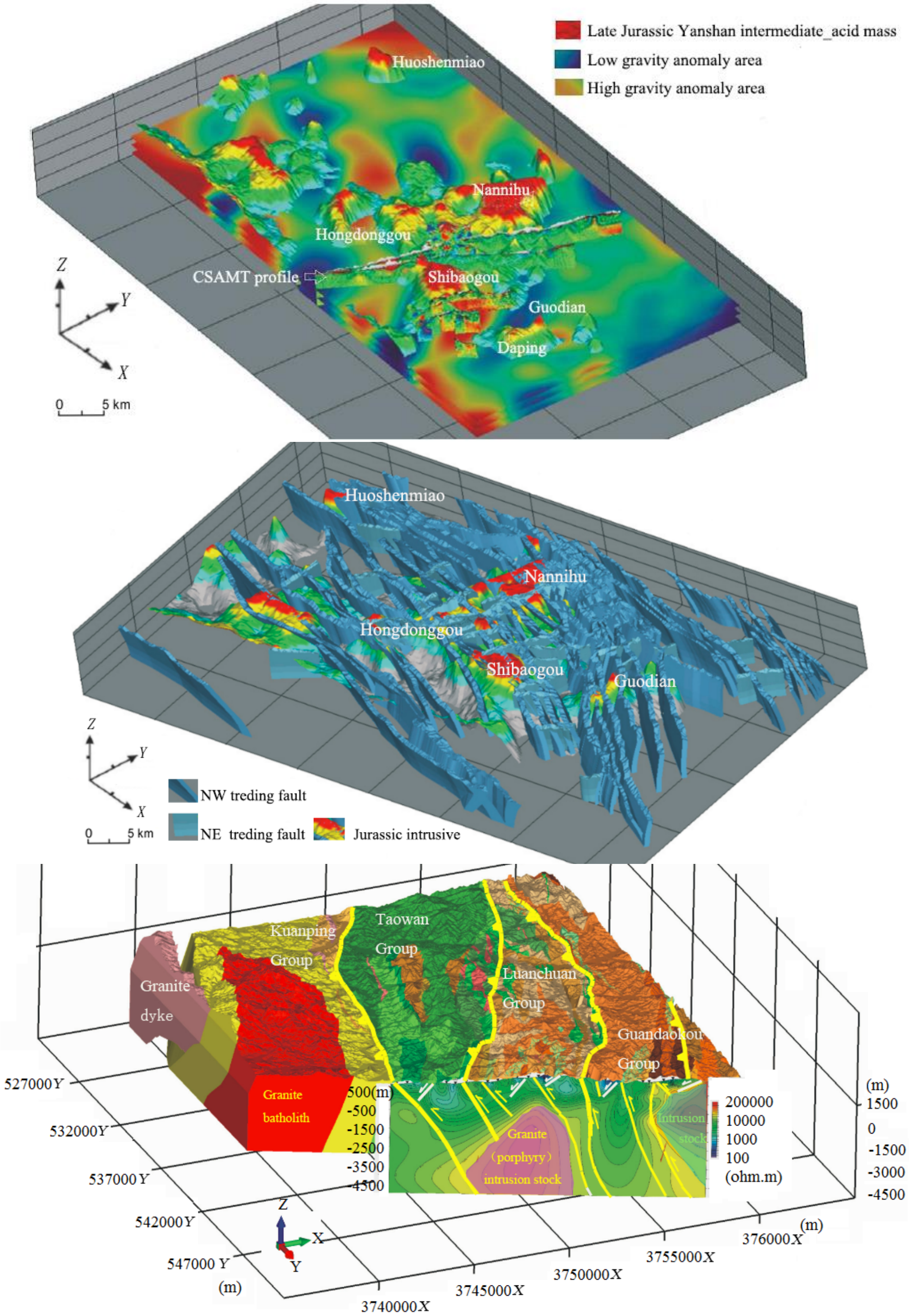

Fig. 3. The geological and geophysical datasets and 3D modeling using Loop joint interpretation [15]
Рис. 3. Наборы геолого-геофизических данных и 3D-моделирование с использованием совместной интерпретации Loop [15]

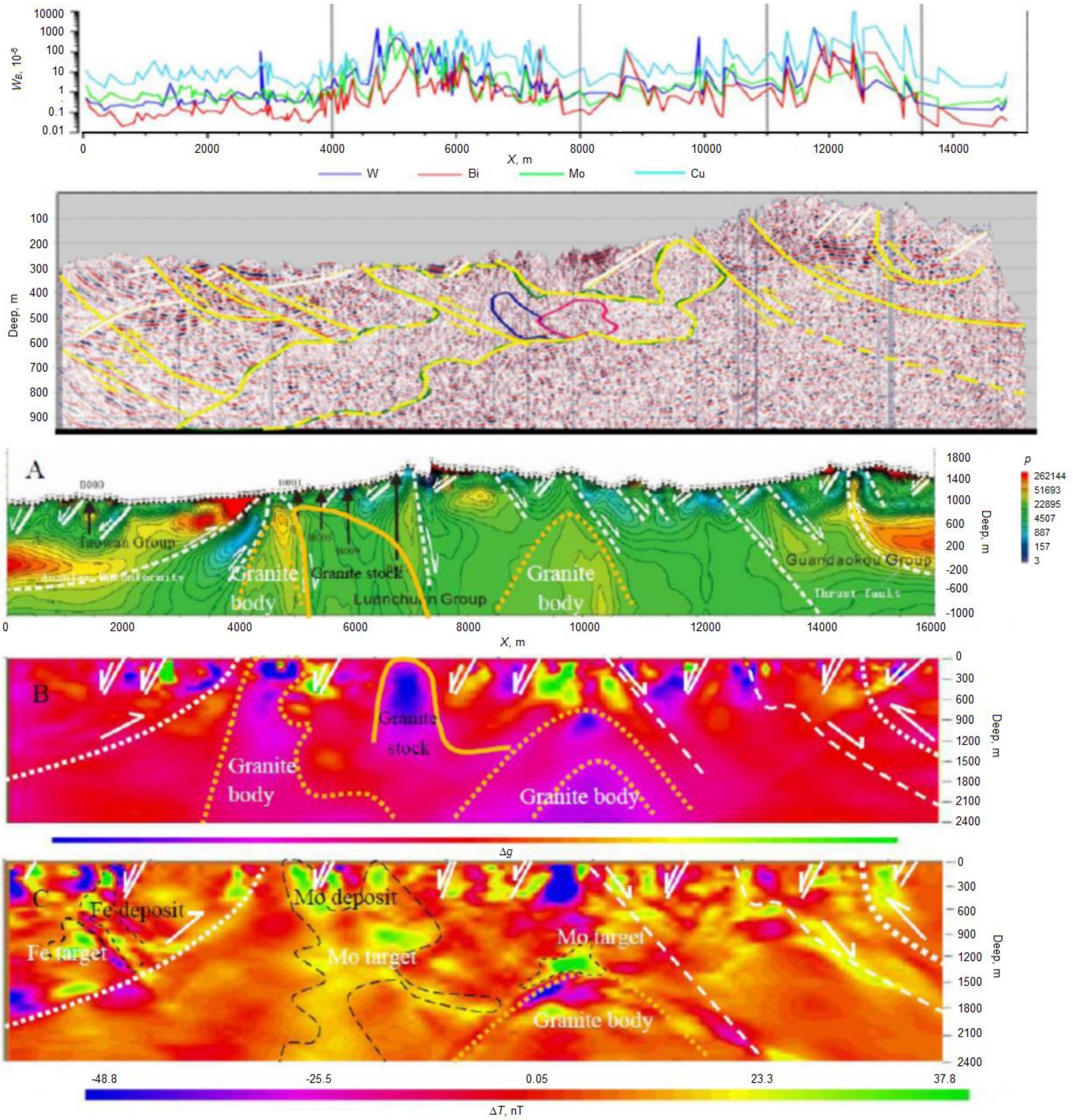

Fig. 4. The geochemical and geophysical datasets to identify key metallogenic bodies in multiple exploration zones

Рис. 4. Наборы геохимических и геофизических данных для определения ключевых металлогенических тел в нескольких зонах разведки

The mine environment evaluation. The mine environment correlated with the geological setting, mining development including three large Mo-W pits and Pb-Zn subsurface channels, and >200 tailings ponds in the study area (Fig. 7). There are four main factors related to mine environmental assessment, which are summarized as geological environment background, mining development, mine geological environment problems, and geological disasters. The geological environment includes structural geology (such as complex structure, strong fault structure development, and joint development), hydrogeology and engineering geology; the mine geological environment problems include aquifer damage, water pollution, and soil pollution; the mine density, open stope area, slope and waste rock treatment of mining development [53–55]; The frequency of secondary disasters in geological disasters is related to the above three.

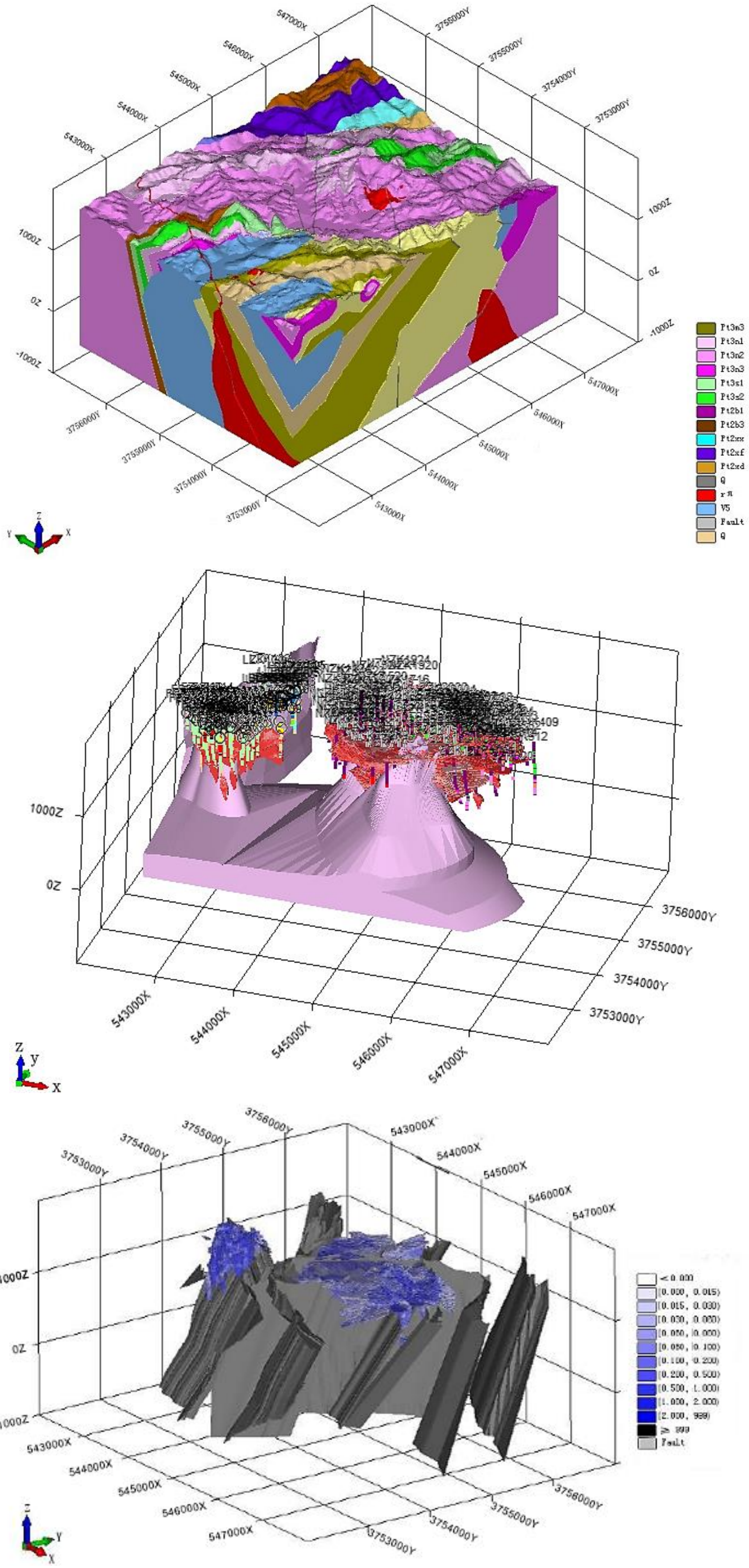

Fig. 5. The 3D geological and orebodies model located in the three large Mo polymetallic deposits (Nannihu, Sandaozhuang, and Shangfang) in the study area [15]
Рис. 5. Геологическая 3D-модель и 3D-модель рудных тел, расположенных на трех крупных молибденовых полиметаллических месторождениях (Наннихy, Сандаочжуан и Шанфан) в районе исследования [15]

a

b

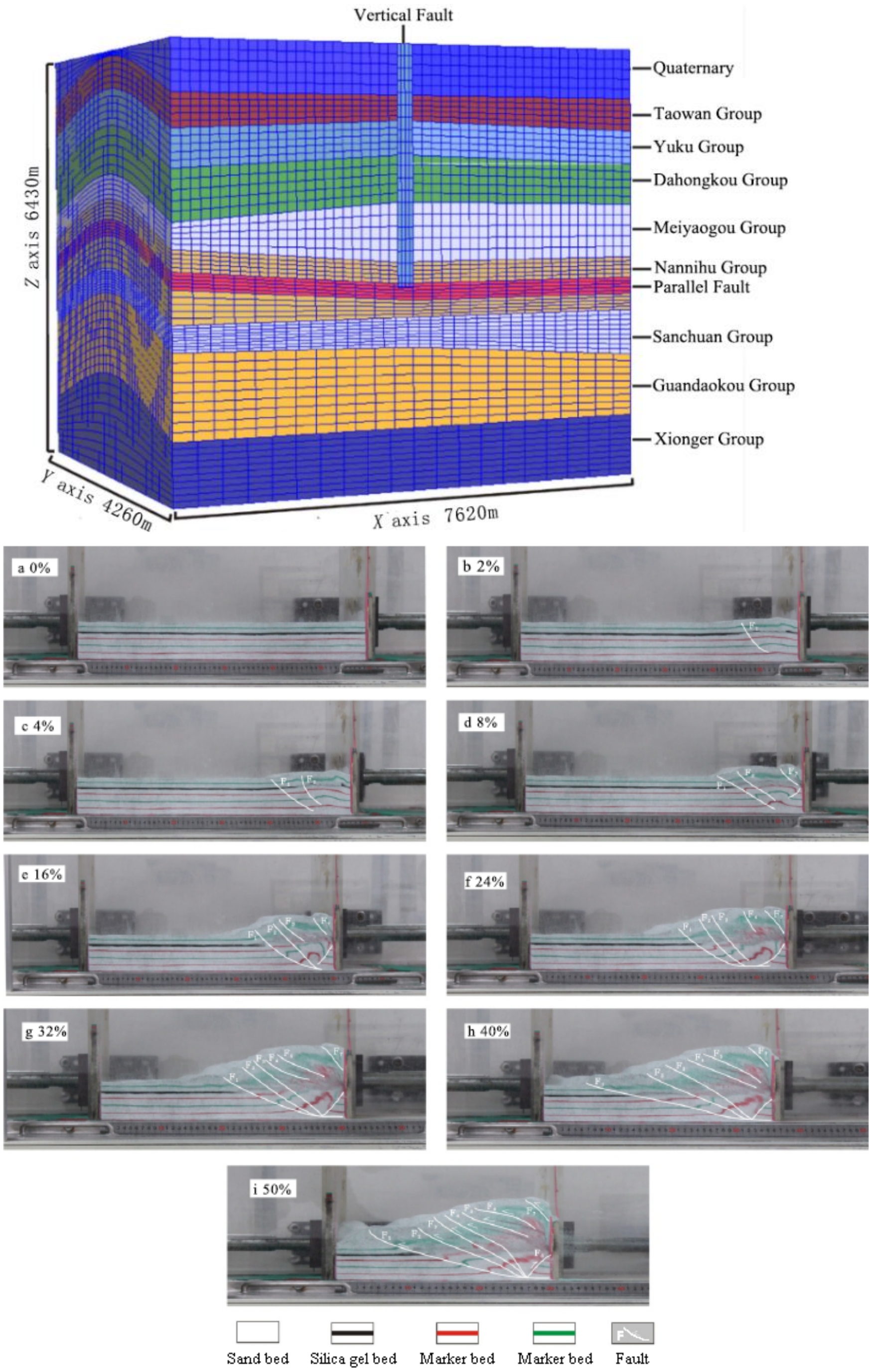

Fig. 6. The 3D simulation using the Flac3D platform and experimental metallogenic dynamic laboratory to analyze the 3D metallogenic model in the study area
Рис. 6. Трехмерное моделирование с использованием платформы Flac3D и экспериментальной металлогенической динамической лаборатории для анализа трехмерной металлогенической модели в районе исследования

In terms of mine environment assessment, remote sensing multi-temporal high-resolution and hyperspectral technology and GIS remote sensing monitoring of mine geological environment, Beidou global positioning system and GPS associated mine micro-seismic monitoring, real-time radar pit, and land subsidence dynamic monitoring, and UAV multi-stage geophysical multi-parameter dynamic monitoring has been demonstrated in mines of the study area.

The mine geological environment in the Luanchuan ore concentration area has serious environmental problems before 2010. The ore fields in the Sandaozhuang, Nannihu, and Shangfang Mo-W deposits, the Luotuoshan polymetallic deposits, and Lengshuibeigou lead-zinc deposit are

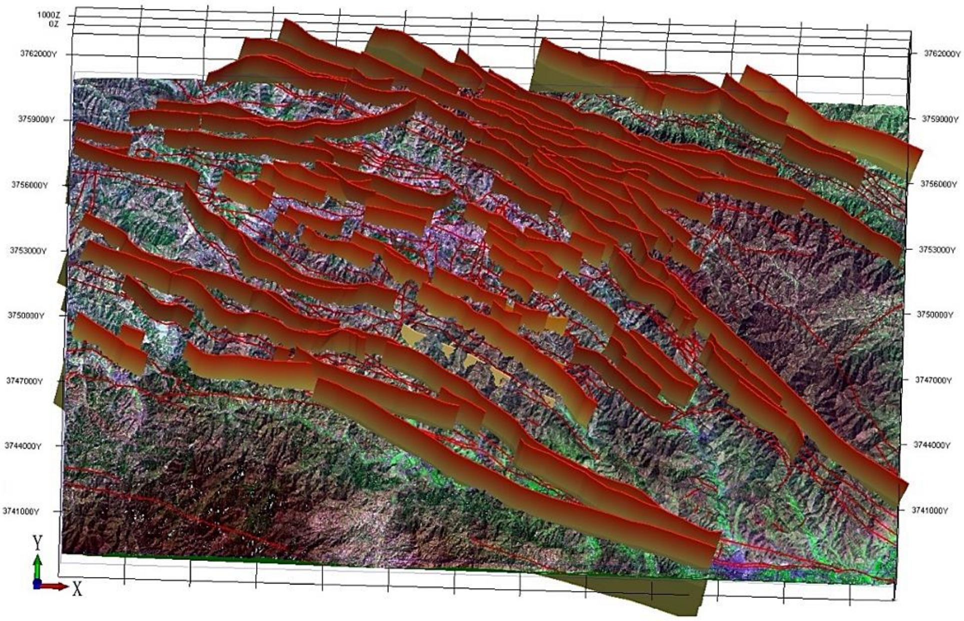

Fig. 7. The 3D NW-trending ore-controlling faults model with different dips and overlay the remote sensing image in the study area

Рис. 7. 3D-модель рудоконтролирующих разломов северо-западного простирания с разными углами наклона, наложенная на изображение дистанционного зондирования в районе исследования

too centralized, resulting in serious groundwater pollution of the Lengshui Town, extensive coverage of soil dust, and even a microclimate of local mineral dust haze in the open stope [56]. Chitudian Pb-Zn deposit is widely distributed, with hundreds of stolen mining holes, and the current situation of historical problems is worrying. After decades of underground disorderly mining in the early years, a large number of extremely complex underground mining caves had been formed under the Sandaozhuang pit. At present, Luanchuan district has 5 five large and medium-sized tailing ponds associated with Mo (W) mines (Fig. 8), more than 100 small and medium-sized polymetallic tailing ponds, and more than 20 deposits undermining. Therefore, the environmental assessment of mining development needs real-time supervision and even 4D control of digital and green and wisdom mines.

According to the characteristics of high mining density and wide distribution of tailing ponds in the study area, the iron alteration of the Nannihu camp with 0.5 m resolution of Worldview2 image is extracted by using remote sensing geoscience Envi5.4 software. Among them, large tailing ponds and open stope generally contain iron contamination (Fig. 8). It can be seen from the images of tailing ponds associated with Sandaozhuang, Nannihu, and Shangfang Mo-W deposits (Fig. 8) that the tailing ponds with abnormal iron pollution have secondary utilization space. In view of the system that needs to increase the minimum beneficiation index of tailings, restrict the diffusion of harmful elements (water and dust) that are soluble in water such as Sb and Hg in multiple ways.

In order to avoid water and dust pollution, closed beneficiation technology and wastewater recycling technology provide technical guarantees for the construction of green mines. The fourth generation of industrial reform and innovation of Luoyang Mo mining group leads and has a number of green beneficiation technology patents, which has preliminarily realized the environmental protection and treatment of mine dust.

Results

The optimization of deep targets and evaluation of mineral resources in Luanchuan district (500 km^2, 2.5 km deep) have been realized as the following aspects:

(1) The Luanchuan Mo polymetallic district has 6.5 million tons of Mo, 1.5 million tons of W, and 5 million tons of Pb-Zn-Ag using the big data integration 3D targeting (the depth is 2500 m) with boreholes dataset and channel engineering dataset, geophysical and geochemical datasets (Fig. 9, Table).

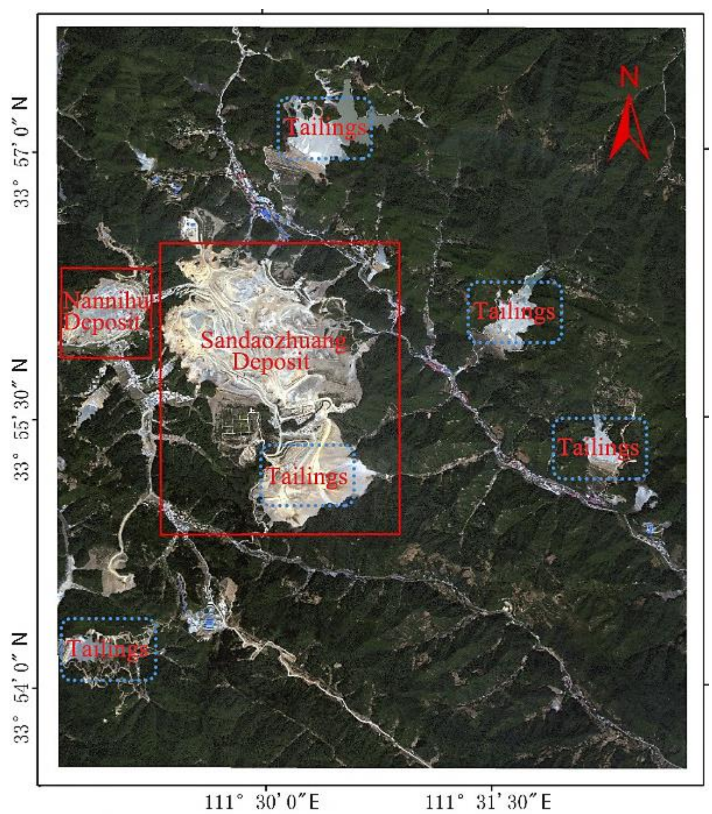

Fig. 8. The Worldview 2 images (0.5 m resolution) in the main deposit zones
Рис. 8. Снимки Worldview 2 (разрешение 0,5 м) в основных зонах месторождения

(2) The mining of subsurface moderate and small Pb-Zn deposits generally affects the surface and subsurface water pollution where secondary NE-trending faults exist, but the large Mo-W deposits with pit mining have little effect on the environment which have a series of geological protection, mining monitoring, and real-time control of geological disasters. The regional NW-trending compression torsion structures have stable geological body features including large nappe structure framework, batholith, and stocks development, but the NE-trending faults have active and tensional features (Figs. 10 and 11).

(3) The NW-trending and NE-trending faults are key factors to control the Mo-W mining pits and subsurface Pb-Zn mines in the study area, and the late NE-trending faults related to mineralization can lead to the subsurface water pollution in the Pb-Zn deposits which are near to the Mo-W porphyry-skarn deposits.

(4) Figure 10 shows the intelligent control of digital mine obtained by tailings pond in Chitudian town. Deep mining serves the sustainable development of mining enterprises through accurate 3D ore body modeling and accurate roadway design (Fig. 10), and green mining technology promotes the rational development and utilization of tailings ponds.

Conclusions

(1) Geoscience big data and artificial intelligence technology provide an opportunity for the development of new theories, technologies, and methods of earth observation and information extraction, promote the development of geoscience theories and methods from qualitative description to quantification, visualization, simulation analysis, virtual reality, and even artificial intelligence, and become one of the effective ways for the joint evaluation of mining development and environment. It provides scientific and technical support for the construction of "green mine, digital mine and smart mine" of "real-time mining". The Luanchuan geoscience big data used in this paper relates the research contents of two first-class disciplines: geology, geological resources, and geological engineering, covering geology, deposit, exploration, hydrology, engineering, mining, beneficiation, mine safety, and other disciplines. Its multi-temporal remote sensing images, dynamic mining information, hydrological environment

monitoring, and other monitoring have the dynamic characteristics of big data.

(2) Using three-dimensional visualization technology and mathematical modeling method, this paper analyzes the genetic model of deposit scale correlation ore field and even ore concentration area scale and constructs three-dimensional exploration variables, including: (a) use

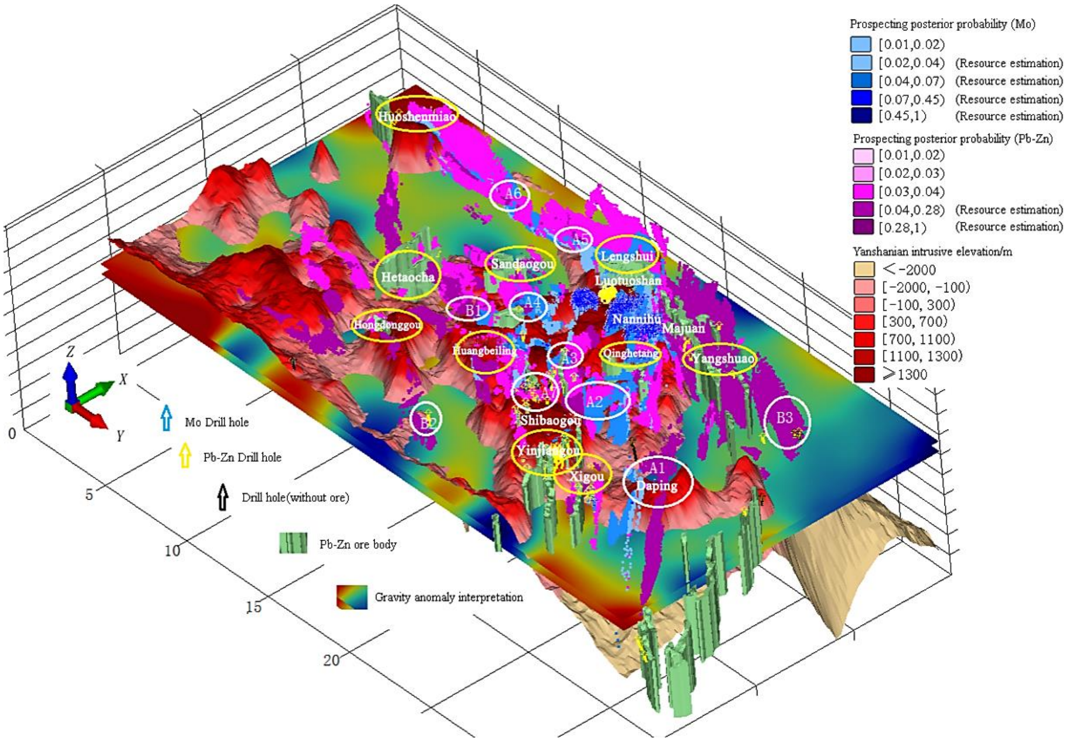

Fig. 9. The Mo and Pb-Zn-Ag priority targeting using GeoCube software in Luanchuan district
Рис. 9. Определение приоритетных целей по Mo и Pb-Zn-Ag с использованием программного обеспечения GeoCube в районе Луаньчуань

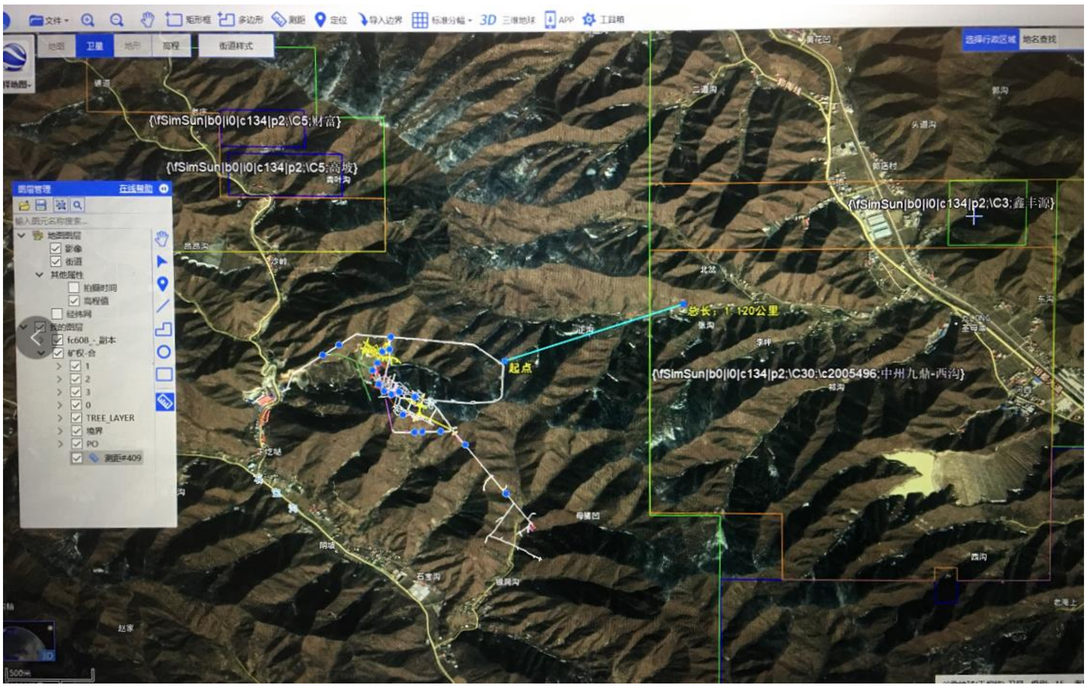

Fig. 10. Digital mine 3D platform based on high resolution remote sensing and channel engineering in Chitudian deposit in Luanchuan district
Рис. 10. Цифровая шахтная 3D-платформа, основанная на данных дистанционного зондирования высокого разрешения и проектирования каналов на месторождении Читудиан в районе Луаньчуань

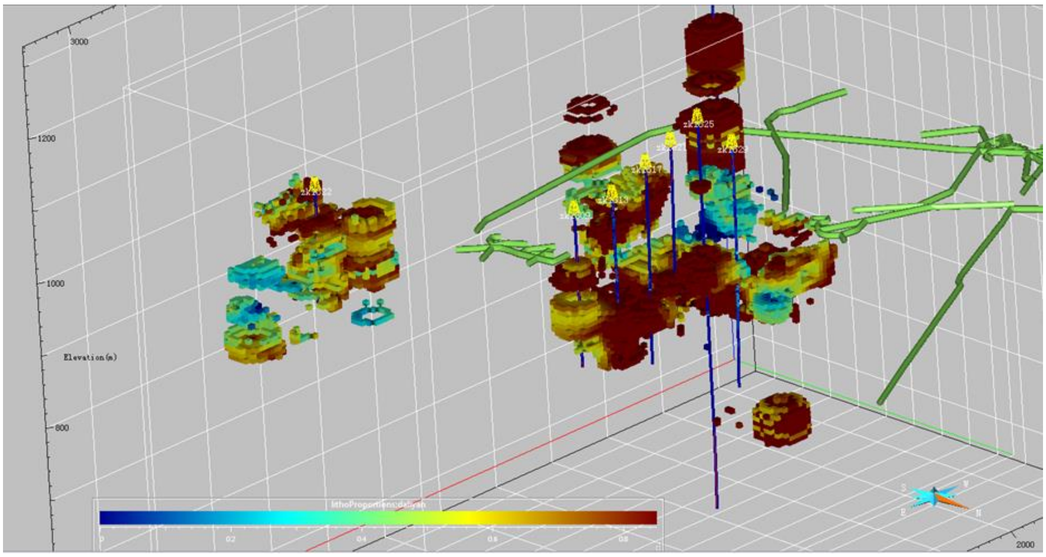

Fig. 11. Three-dimensional engineering model of high-precision exploration drilling, orebody and channel mining in Chitudian Xigou lead-zinc Mine (location in Fig. 10)
Рис. 11. Трехмерная инженерная модель высокоточного разведочного бурения, разработки рудных тел и каналов на свинцово-цинковом руднике Читудиан Сигоу (расположение см. на рис. 10)

geological and geophysical forward and inverse modeling method assisted by rock geochemistry to comprehensively interpret metallogenic terranes. It can better identify the favorable sections of concealed granite porphyry and porphyry-skarn Mo-W mineralization in Yuku, so as to provide an important basis for subsequent deep prospecting practice and exploration engineering deployment; (b) Flac3D simulation is used to analyze the geometric shape and influence domain of three-dimensional intrusive rock mass, which can deeply analyze the metallogenic system of porphyry Mo, skarn Mo (W) and hydrothermal Pb-Zn-Ag-Au ore bodies, so as to provide a scientific basis for the comprehensive evaluation of digital mine resources; (c) using high-resolution remote sensing to extract iron pollution information and correlate mining pollution can dynamically monitor the treatment and restoration of ecological environment.

(3) Using the metallogenic system theory, combined with the multi-parameter and multi-method modeling of three-dimensional metallogenic geological body, it is better to reveal the Shibaogou porphyry Mo deposit in the Chitudian area. Temporal and spatial distribution of skarn Mo-W-Zn-Pb deposits and the distal Yindonggou and Xigou hydrothermal Pb Zn Ag Au deposits and quantitative evaluation of resources [6]: Mo (W) industrial ore bodies are built from 1200 m to 400 m above the surface, and the vertical depth of lead-zinc ore bodies is 600 m; The deep Mo-W prediction target area in the Yuku section is 2.5 km, which is the most favorable section for Mo (W) prospecting in the ore concentration area and the section with the largest value of industrial ore body. The main concealed ore body is 200 m below the surface.

(4) Based on the 3D models of geological bodies such as strata, fault structures, and ore bodies in the Luanchuan ore concentration area, it is recognized that the NW-trending fault structures usually have compression and torsion characteristics, which inherited the thrust nappe tectonic environment in the southern margin of the North China Craton, and the groundwater pollution in the metallogenic section of the existing mines is not developed. After the metallogenic period, the fault structure cuts through the surface, resulting in the infiltration of surface water into the mining section, resulting in secondary hydrogeological pollutions, and even erosion, resulting in geological disasters such as mining roadway collapse. Therefore, in terms of hydrogeology, it is necessary to avoid the excavation of NE structures, prevent the water pollution of NW-trending ore bodies, and take ban measures when necessary. In addition, the vein-type Pb ore body in the east of Chitudian area which is in the east of the southwest section of Shibaogou Mo polymetallic deposit should be avoided as much as possible at the intersection of NW trending

nappe structure and its associated NE trending fault structure for the mining of Zn ore body, because it is usually the collection section of groundwater sources, it is necessary to avoid groundwater disorder and pollution.

(5) The modeling and analysis of three-dimensional multi-parameter (geological, geophysical, geochemical, and hyperspectral) geological bodies in the study area greatly improves the reliability of borehole core logging and the mining of quantitative massive information and enriches the content of lithology logging of previous exploration boreholes. For example, hyperspectral core scanning in the Shangfang deposit, from exploration mineralogy to beneficiation process mineralogy, has laid the foundation for real-time mining. In recent 20 years, China's mineral survey and exploration have accumulated a large number of core data. Using the data mining of core physical properties, lithology, and spectral continuity, we can systematically carry out deep prospecting and resource evaluation in the study area: such as the mining and development of useful elements, including the exploration, development, and application of associated elements such as Cu, Ag, Au, and Re; Analysis of harmful elements (As, Sb, Hg, S): prevent man-made disasters in the mining industry, such as pollution of waste ore and pollution of tailings pond dust to air, groundwater, surface water, and soil.

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Гунвэнь Ван – профессор Китайского университета наук о Земле (Пекин). Получил степень бакалавра в области разведки полезных ископаемых в Северо-Восточном университете Китая в 1993 году, степень магистра в области математической геологии в Китайском университете наук о Земле в 2000 году и там же в 2006 году получил докторскую степень в области исследования Земли и информационных технологий. Работает в Школе наук о Земле и минеральных ресурсов Китайского университета наук о Земле с 2000 года. Его исследовательские интересы сосредоточены на 3D/4D-моделировании для оценки минеральных ресурсов и окружающей среды с использованием больших массивов геологических данных и искусственного интеллекта.

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