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In-Situ Leaching Mining Technique for Deep Bauxite Extraction and the Countermeasures for Water Pollution Prevention: An Example in the Ordos Basin, China

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Abstract: As the second most significant metal following steel, aluminum plays a vital role in the advancement of both strategic emerging industries and national economic development. The existing oil and gas drilling data indicate that the deep bauxite deposits is abundant around the Ordos Basin in China, at the depths ranging from several hundred meters to several kilometers. Based on the geological and hydrogeological characteristics analysis, it is found that deep bauxite deposits in the basin have distinct electrical characteristics, characterized by *four highs and two lows.* While there is scarcity of prior research on the exploration topic for the technique limitation. In this paper, a logging interpretation model has been developed, which allows the evaluation of bauxite deposits. An efficient technology was proposed for deep bauxite exploration, utilizing an in-situ leaching mining technique. This technology is well-suited to the geological conditions of the Ordos Basin, ensuring that the solution flows within the bauxite ore bed without any seepage loss. To prevent the leaching solution from seeping into and polluting the main aquifer around the basin, several measures have been proposed. These include filling with polymer resin, well pattern seepage control plugging, and establishing monitoring systems. The results of this study provide a theoretical basis for the adoption of environmentally sustainable mining techniques and the mitigation of water pollution in deep bauxite exploration.

Keywords: bauxite; occurrence state; microstructure; nuclear magnetic resonance; water pollution prevention and control; in-situ leaching technique

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1. Introduction

Bauxite, the primary source of metallic aluminum, is composed of aluminum-bearing minerals, iron-bearing minerals, and small amounts of silicates, titanates, sulfates, and carbonates [1–3]. In-situ leaching mining is a novel mining method. It utilizes the physical and chemical properties of minerals to selectively dissolve, leach, and recover useful mineral components by injecting water, chemical solvents, or microorganisms into the deposit or heap [4,5]. This technology is commonly employed in the mining of salt, uranium, and rare earth ores. For instance, water-soluble mining of salt mines can be traced back over 1400 years. It remains in use today due to its efficiency and cost-effectiveness. In 1961, Soviet hydrogeological engineers designed an in-situ pumping test for a sandstone uranium mine that achieved a 77% uranium recovery rate by 1978. Similarly, the United

States conducted a series of successful in-situ leach uranium mining experiments during this period. It leads to the mainstream adoption of this process in the U.S. uranium mining industry by 1992 [6]. While attempts at in-situ leaching mining of other non-ferrous metals were made as early as the 16th century in Spain, large-scale application was not feasible due to industrial limitations at the time. In 1995 a project study of in-situ copper mining was conducted in Santa Cruz, Arizona, USA. Copper ore below 370 m was successfully extracted from the ground through field trials with acid dissolution. The project delivered 25 gallons of saturated solution per minute and yielded 1 ton of copper output per day [7], demonstrating the commercial viability of this technology. Recently, Kongar (2023) describes the possibility of leaching of metals from geo-raw materials. The sequentially-selective extraction of metals from raw materials by changing the alkalinity (pH factor) of the agent is proposed, which significantly increases the extraction of the valuable component, reduces the agent consumption and increases the economic efficiency of the leaching method used [8]. Researchers studied the leaching process and achieved the maximum extraction of the valuable component from the geo-raw materials [9]. The studies on the extraction of the valuable component from the geo-raw material by leaching were carried out with different activation times and irrigation of the working solution with hydrochloric acid of differential concentration.

Throughout the history of in-situ leaching technology, its most mature and widely used applications is in the mining of uranium and rare earth elements [10,11]. The use of this technology for the extraction of other metal minerals has been less prevalent. In recent years, gas has been obtained from the bauxite layer during oil and gas exploration, challenging previous assumptions that the dense bauxite layer could only serve as a regional cap layer [12]. Furthermore, it has been confirmed that bauxite is an effective reservoir due to the development of microfractures and dissolved pores, which create a well-connected pore network. Motivated by the results of previous research, this study introduces the conception of the in-situ leaching mining technique for extracting deep bauxite deposits. The approach is grounded in a comprehensive analysis of the geological attributes and petrophysical properties of bauxite deposits located within the Ordos Basin.

The Ordos Basin is one of China's most significant energy reserves, boasting abundant resources such as oil, gas, coal, bauxite, uranium, rock salt, oil shale, cement limestone, mirabilite, and gypsum. The proven reserves of natural gas, coalbed methane, coal, uranium, and rock salt within the basin rank first in China, while its proven petroleum geological reserves rank fourth. The basin contains rich bauxite resources with proven reserves of 770 million tons. These resources are primarily distributed across Shaanxi, Shanxi, Inner Mongolia and Gansu provinces [13,14]. Numerous scholars have investigated the distribution, genesis, classification, and geological characteristics of typical bauxite minerals in the periphery of the Ordos Basin [15–17]. However, research on deep bauxite deposits within the basin remains limited. Oil and gas drilling data indicate that the basin contains rich bauxite resources at depths ranging from several hundred meters to several kilometers. The exploration and exploitation of deep bauxite could greatly alleviate the national shortage of bauxite resources.

By 2015, six in-situ leach uranium mines were constructed in China, primarily utilizing acid leaching methods. In an effort to reduce the pollution of shallow and groundwater, new types of neutral leaching and microbial leaching have been gradually implemented in recent years [18]. Researchers focuse on minimizing the impact of productive brines on the environment. The authors investigated the penetration of these brines through the fracture system into the mass, established the radius of penetration and proposed a way to isolate the sources of contamination [19]. There are also research formulates a multifactorial mathematical model of degradation of environmental ecosystems as a result of the impact of waste [20]. Considering the geological profile of the Ordos Basin, this paper examines the implementation of a barrier layer to inhibit leachate infiltration into the aquifer. This is achieved through the utilization of well network seepage control and the injection of polymer resin. Furthermore, the establishment of a dynamic monitoring system at the mining site is proposed, to continuously track and assess groundwater conditions, thereby preventing and mitigating water pollution. The research aims to provide a theoretical foundation for the exploration and environmentally sustainable extraction of deep bauxite deposits within the Ordos Basin.

2. Characteristics of Deep Bauxite in the Ordos Basin

2.1. The Geological Characteristics

2.1.1. Formation of Orebearing Rock Series

Bauxite within the Ordos Basin is found in aluminiferous rock series in the middle and lower portions of the late Carboniferous Benxi Formation. The Benxi Formation consists of early Late Paleozoic sediments deposited on a basement geomorphology shaped by Caledonian Ordovician erosion and weathering. Sedimentation primarily occurred through filling and supplementing low and concave paleogeomorphology on the weathering surface. Sedimentary thickness, which generally ranges from 10 to 80 m, is mainly controlled by paleogeomorphology and tends to be thicker in the east and thinner in the west.

The rock types of the Benxi Formation are mainly bauxite of weathering products, clastic rock of littoral and shallow Marine facies, tidal flat limestone of littoral marsh facies, coal rock and carbonaceous mudstone, which are characterized with ferro-aluminite assemblages containing pyrite and siderite nodules or bands. Vertically, the Benxi Formation can be divided into Member 1 and Member 2 (Figure 1). The lithology of the upper part of Member 1 is mainly dark gray micritic limestone and coal seam, mixed with gray coarse sandstone and pebbled coarse sandstone. The natural gamma is low and massive, while the deep and shallow lateral resistivity is high and massive. The lower part of the Member 1 is mainly dark gray mudstone, interbedded with thin gray sandstone and limestone. The natural gamma is medium-high, micro-dentate and local finger. The lithology of the upper part of the Member 2 is gray, light gray medium-coarse sandstone and dark gray mudstone, partially interbedded with thin micritic limestone. The natural gamma is medium-high value, dentate, partially massive, and the resistivity is mainly low value. The lithology of the middle part of the Member 2 is dark gray mudstone, light gray conglomerate and pebbly coarse sandstone. The natural gamma is dominated by high value, weakly dentate, locally low value and massive, and the resistivity is dominated by medium and low value. The lower part of the Member 2 is high gamma-aluminum mudstone, whose thickness is generally 3~6 m, and the lower part is Majiagou Formation limestone or dolomite.

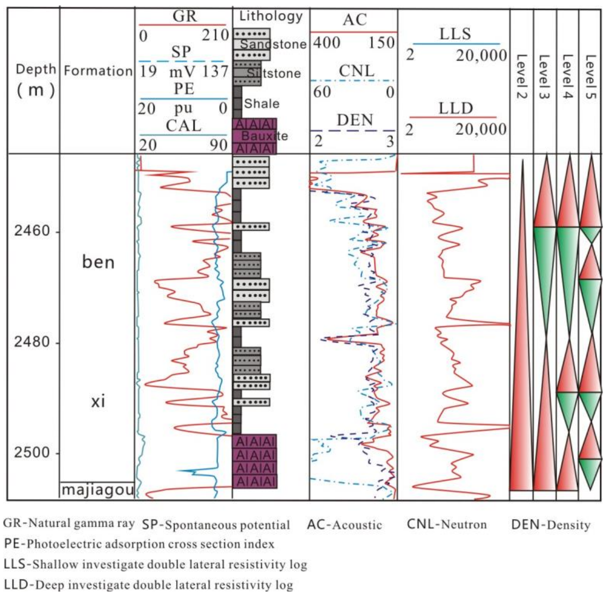


Figure 1. Sedimentary characteristics of Benxi Formation.

2.1.2. Structure and Thickness Variation of Bauxite Layer

On the paleoerosion surface of Ordovician carbonate rocks, the vertical aluminiferous rock series exhibits a sandwich structure. Specifically, bauxite is often found between top and bottom layers of clay rock or shale. The aluminiferous rock system developed on an unconformity surface where the basement rock is typically carbonate. The bottom layer consists of aluminum iron bauxite and bauxitic mudstone with poor physical properties and a thickness of 2–4 m. The middle layer consists of bauxite and porous bauxite with better physical properties and an average thickness of approximately 6.3 m. The upper layer consists of black carbonaceous mudstone with poor physical properties and a thickness of 1–2 m (Figure 2).

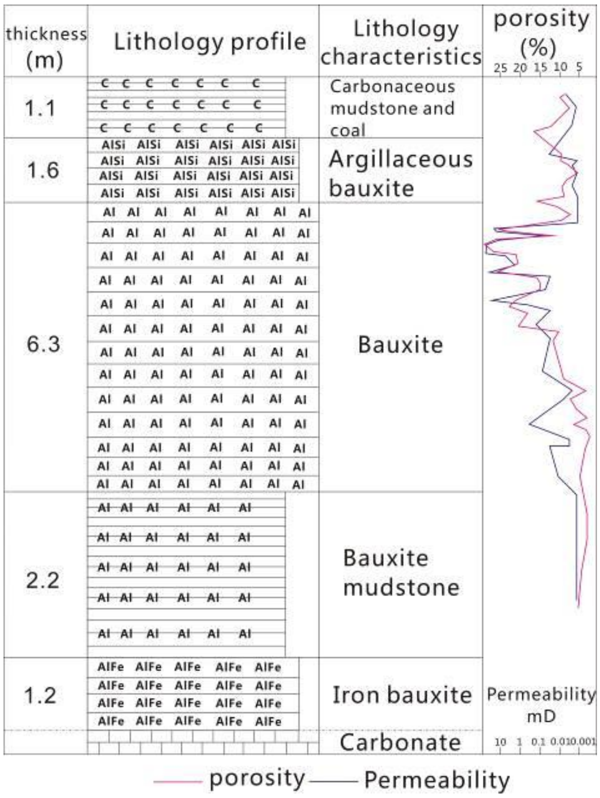


Figure 2. Sedimentary Sequence and Vertical Physical Properties of Bauxite in Benxi Formation.

The distribution of the bauxite is controlled by karst palaeogeomorphology. The palaeoterrain is flat, the orebodies are layered or quasi-layered, and the palaeoterrain is uneven and mostly lens-shaped. On the plane, the bauxite is mainly deposited in low and concave paleogeomorphic areas, with a banded or lamellar distribution (Figure 3). In the same strip or area, bauxite beds are stably distributed with good continuity (Figure 4). The average thickness of the ore beds ranges from 1.5 m to 3 m, which is positively correlated with the thickness of ore-bearing rock series, with a correlation coefficient of 0.38–0.76.

2.1.3. Electrical Characteristics of Bauxite

Bauxite has obvious electrical characteristics [21], which has been used as an important marker layer at the bottom of Benxi Formation in oil and gas exploration, with unusually high natural gamma (GR), generally above 300 API. The electrical resistivity (LLD, LLM) is generally about 35 Ω/m, with a maximum value of 100 Ω/m. The compensated neutron (CNL) porosity is high, usually about 60%. The density (RHOB) is high, generally around 2.74 g/cm^3, and the acoustic time difference (AC) is low, generally around 170 μs/m (Figure 5).

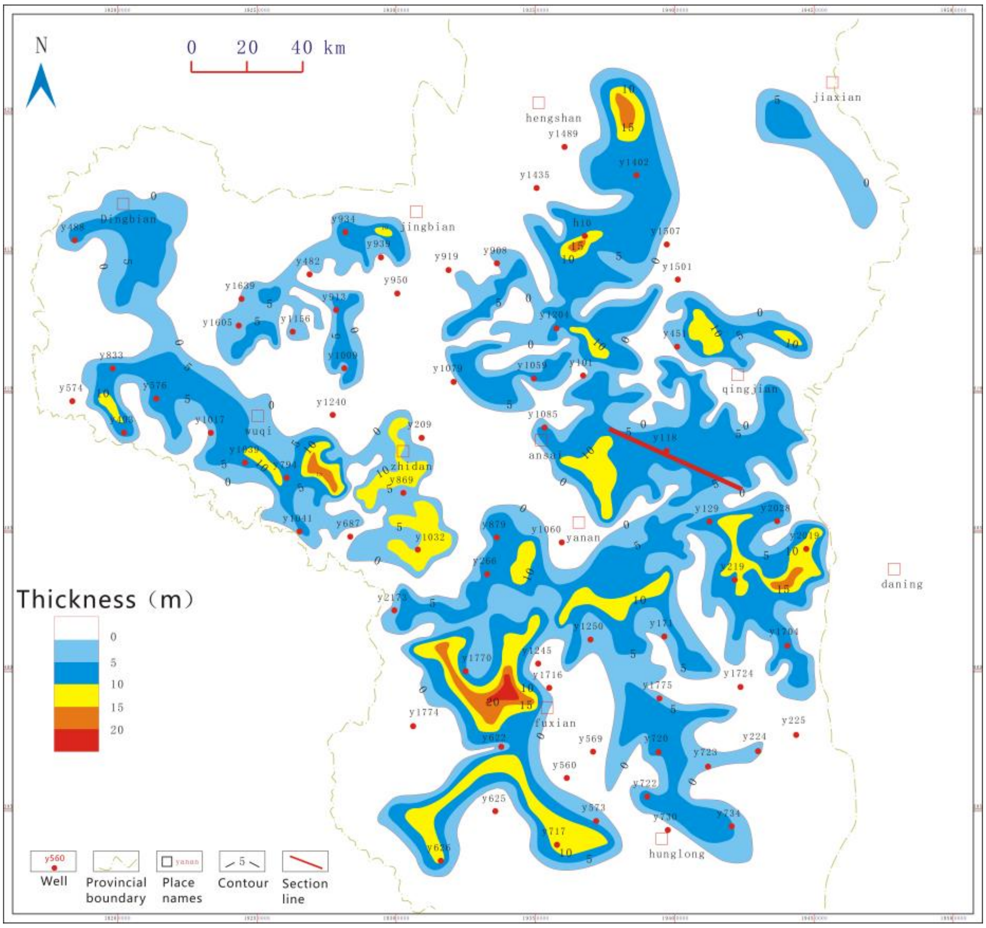


Figure 3. Distribution of bauxite in southern Ordos Basin.

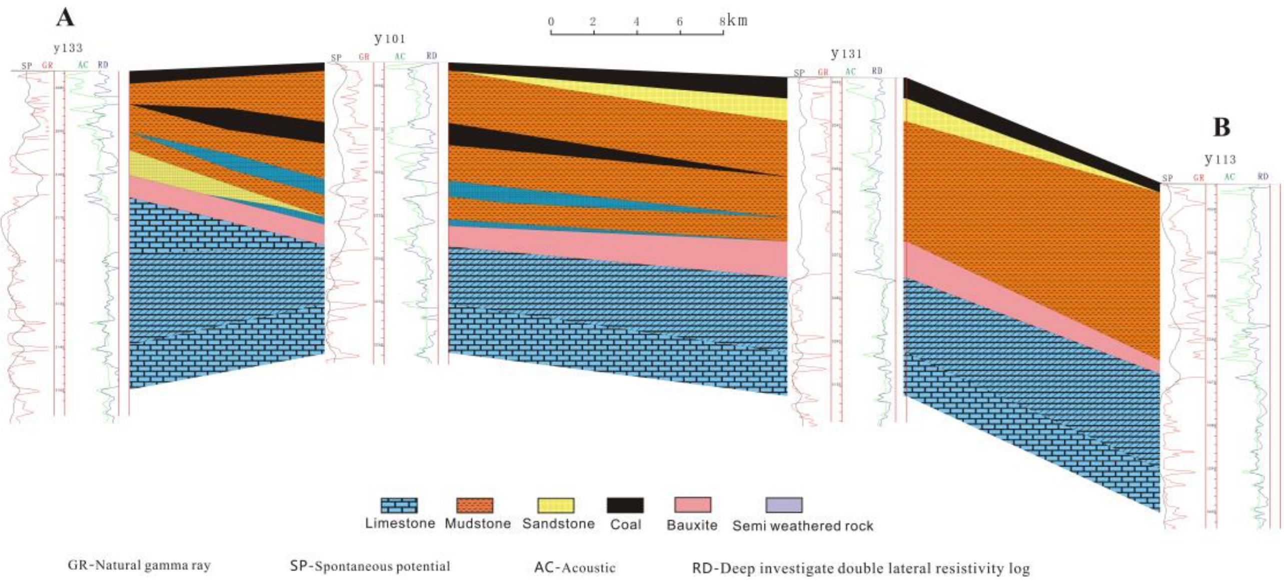


Figure 4. Lithological Structure of Top and Bottom of Bauxite Deposits.

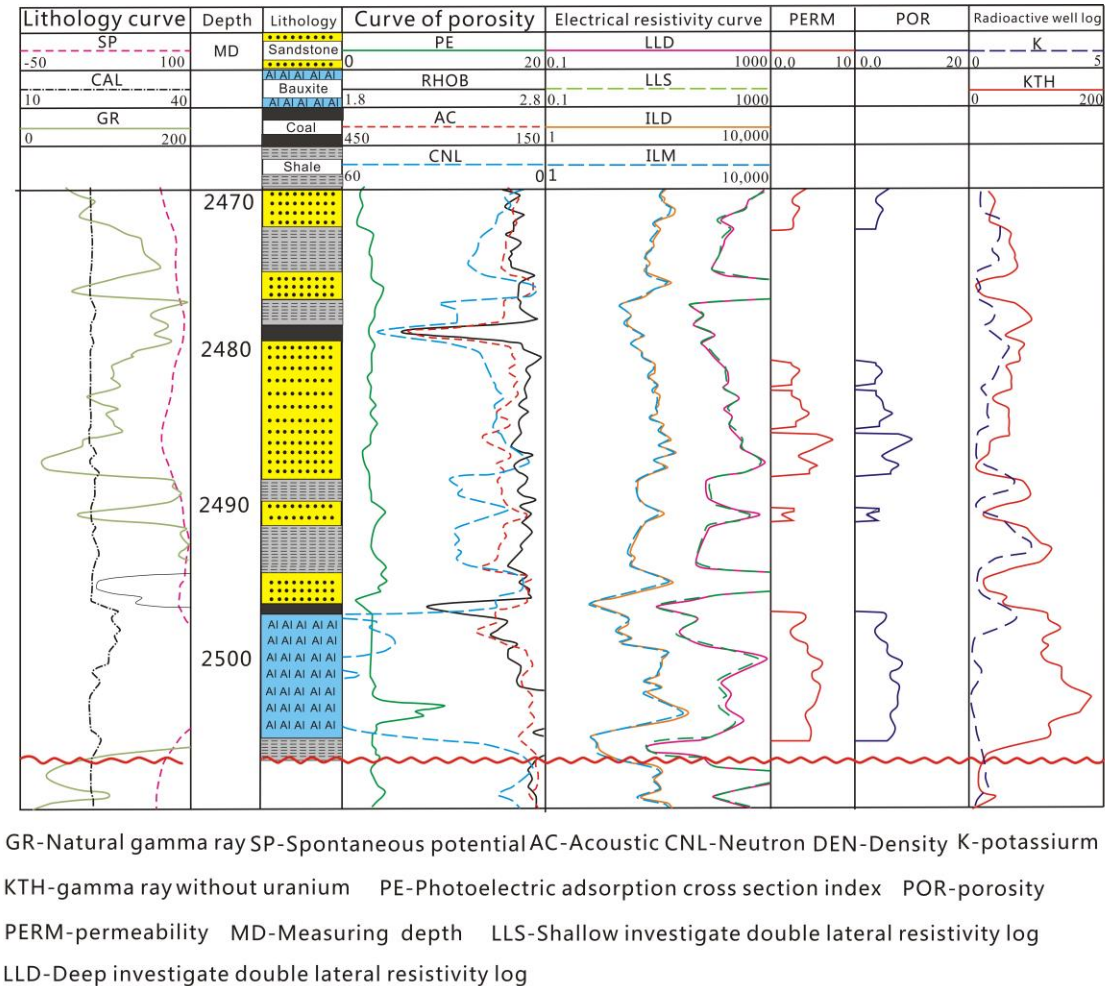


Figure 5. Logging response characteristics of bauxite (taking Yan x well as an example).

Therefore, with the help of core calibration logging, conventional logging and special logging, bauxite identification standard and bauxite logging parameter model can be established, and bauxite evaluation indexes such as diaspore content and aluminum-silicon ratio can be calculated, which can complete the evaluation of the bauxite in great buried depth.

2.2. Hydrogeological Characteristics of Basin and Water Bearing of Bauxite Layer

2.2.1. Hydrogeological Characteristics of the Basin

Ordos Basin is a giant groundwater basin with multiple aquifer systems with different characteristics that are overlaid or linked laterally, cut and connected with each other in different degrees in space [22]. These aquifer systems are composed of a variety of different types of rocks. From bottom to top, they are: Cambrian-Ordovician carbonate karst aquifer system, Carboniferous—Jurassic-Cretaceous sandstone fractured aquifer system, Quaternary loess pore aquifer system and Cenozoic loose rock pore aquifer system (Figure 6).

The groundwater in the Cambrian and Ordovician carbonate strata belongs to the karst-fractured water type (karst water for short), and the Cambrian crystalline rock at the bottom and the carboniferous aluminite shale at the top are the regional water barrier layer. The carbonate rocks in the middle of the basin are buried at a depth of 4000 m. The research shows that the karst water in the carbonate rocks cannot penetrate the basin for deep circulation, and the groundwater stagflation sealing zone is formed in the middle of the basin. The circulation of the modern karst water only occurs in the karst body at a certain depth around the basin (generally buried within 800~1200 m), which is the main aquifer with large water volume and good water quality. It is mainly controlled by climate, topography, lithology and lithofacies, structure, buried depth and karst development.

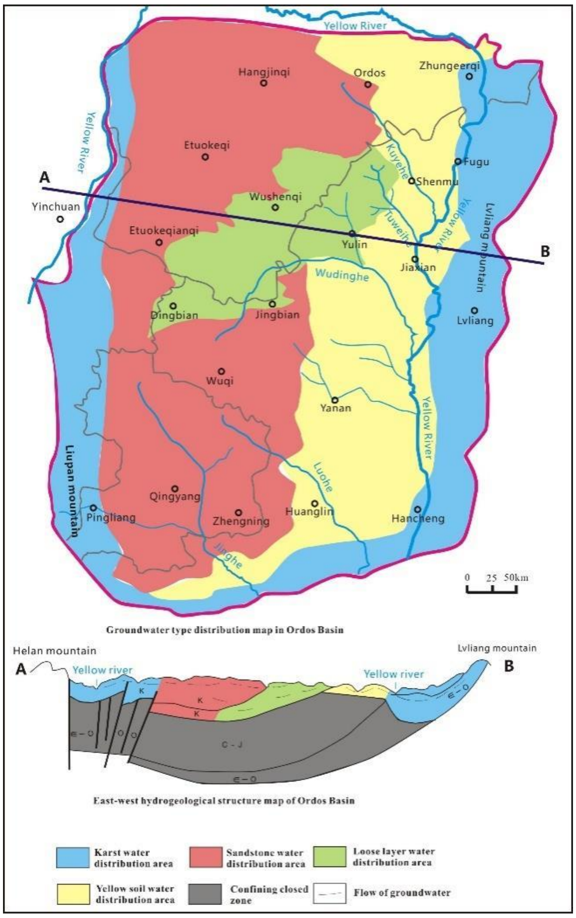


Figure 6. Types and distribution characteristics of groundwater in Ordos Basin.

The main aquifers of loose rocks include Quaternary aeolian and alluvial sand layers, alluvial (flood) sand and gravel layers, and part of loess. The pores of these rock strata play a leading role in water storage and water conduction. The water-bearing medium is relatively uniform, and the occurrence of groundwater is relatively uniform. In the shallow part of the basin, an incomplete continuous plateau pore aquifer system with obvious difference between north and south is formed. Generally speaking, the water quantity is large, and the water quality is good. The basin has a certain mining value, and often become an important water supply source for the severe water shortage areas.

2.2.2. The Bauxite Layer Is Water-Bearing

It is believed that Carboniferous aluminite shale is a regional water-proof layer. The permeability of pure bauxite is (6.50~14.50) $\times 10^{-8}$ μm^2, the permeability of aluminite mudstone is (0.83~6.40) $\times 10^{-8}$ μm^2, and the breakthrough pressure is greater than 5 MPa. The aluminite shale has high expansibility, and it is often associated with argillite. The diagenetic process is not easy to produce fractures, which is an ideal water barrier for gas reservoirs. However, in 2015, Changqing oilfield drilled 9.3 m into the bauxite rock layer of Benxi Formation in Well Shaan 464 in the eastern Ordos Basin. The low-yielding gas flow of 1849 m^3 per day was obtained through gas test, and the bauxite gas reservoir of Benxi Formation was discovered for the first time. In the same year, well D66-172 in the bauxite section of Benxi Formation obtained daily gas of 1.0375 $\times 10^4$ m^3 and daily water of 2.9 m^3. In 2020, Changqing Oilfield conducted a large number of gas tests in Longdong area. Most of the gas wells produced gas and water, with the highest daily water production of 33.6 m^3 and the average daily water production of 18.6 m^3, proving that the local Carboniferous Benxi Formation bauxite has a certain porosity and permeability, as well as a certain water content. The analysis shows that the formation water of Carboniferous Benxi Formation bauxite is mainly confined and retained during the deposition period.

2.3. Microstructure of Bauxite

To gain a comprehensive understanding of the microstructure characteristics of Bauxite, this study focuses on outcrop Bauxite located in the southern region of the Ordos Basin. Utilizing a range of techniques, including casting thin section, X-ray diffraction, scanning electron microscopy, conventional physical properties, and constant pressure mercury injection, the mineral composition and pore structure of the bauxite ore bed were systematically analyzed. The instruments employed in this research include the D8 Focus X-ray diffractometer from Bruker Company (Hanau, Germany), the CMS300 pore permeability tester from Corlab Company (Denver, CO, USA), the 9520 II constant pressure mercury intrusion meter, the QuantaFEG 450 field emission scanning electron microscope from FEI Company (Alhambra, CA, USA), and the 4500P polarization microscope from Leica Company (Wetzlar, Germany).

2.3.1. Mineral Composition and Occurrence State

X-ray diffraction analysis showed that the mineral composition of bauxite ore was mainly diaspore or boehmite, with a content of 40–77%. The secondary clay minerals are mainly kaolinite, with a content of 3–37%. Trace minerals include quartz, feldspar, hematite, anatase, goethite, etc., with a content of 1–11%. Some of the pores are filled with calcite and (iron) dolomite, with a content of 1–6% (Figure 7). Diaspore presents plate-like, needle-like and columnar crystals, and flake and scale forms can also be seen. The flake and scale forms of diaspore are filled between beans and oolitic grains with interstitium. Kaolin is distributed in the core of bean oolitic grains in fine sheets and fibers or mixed with diaspore to form the belt of bean grains and oolitic grains. Kaolin is also used as interstitial material between grains. Calcite and (iron) dolomite are mostly used as interstitial material, occasionally with ingrain cores or ring structures (Figure 8).

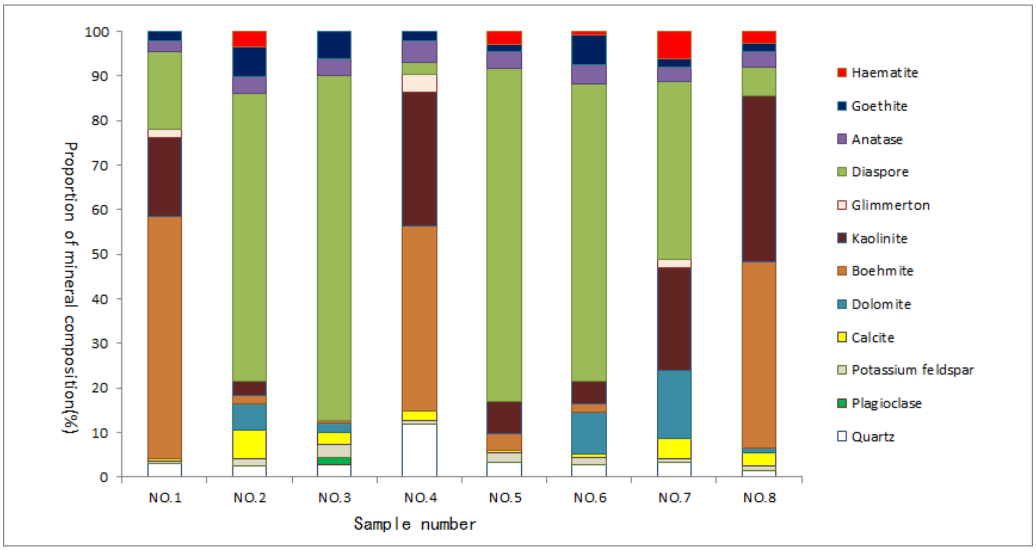


Figure 7. X-ray diffraction mineral composition map of a bauxite deposit in Ordos Basin.

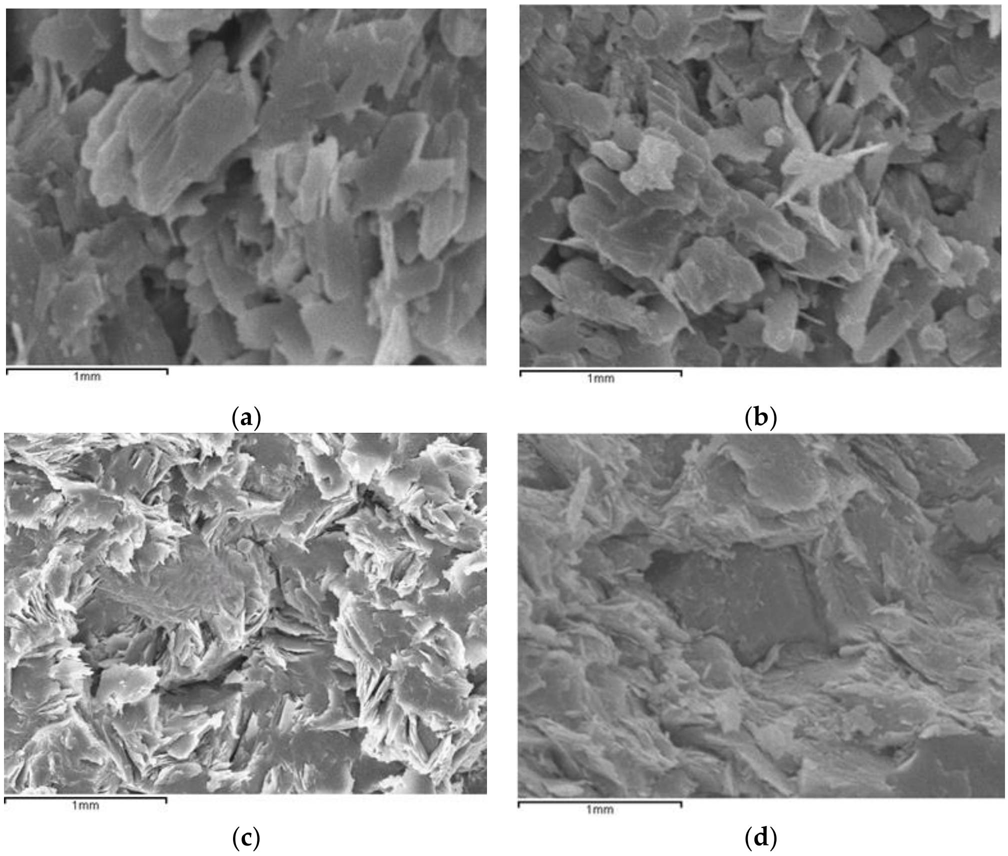


Figure 8. Microstructure of bauxite under scanning electron microscope. (**a**) Compact tabular diaspore. (**b**) Diaspore, anatase. (**c**) Scaly diaspore. (**d**) Fine sheets of kaolin.

The petrochemical components of the bauxite are mainly Al_2O_3, SiO_2, Fe_2O_3, TiO_2, and a small amount of CaO, MgO, K_2O, Na_2O, etc. (Figure 9).

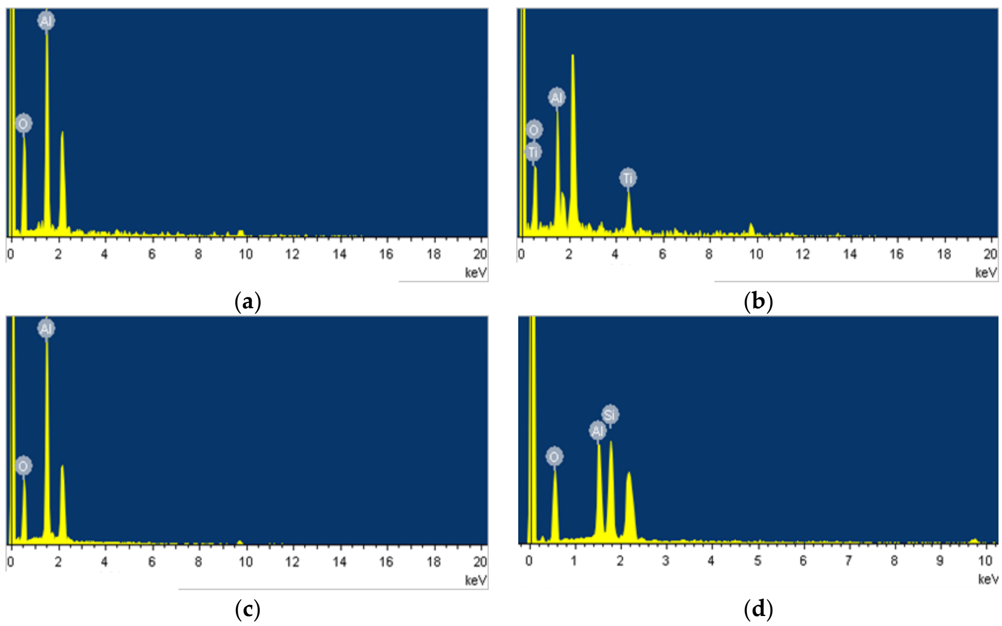
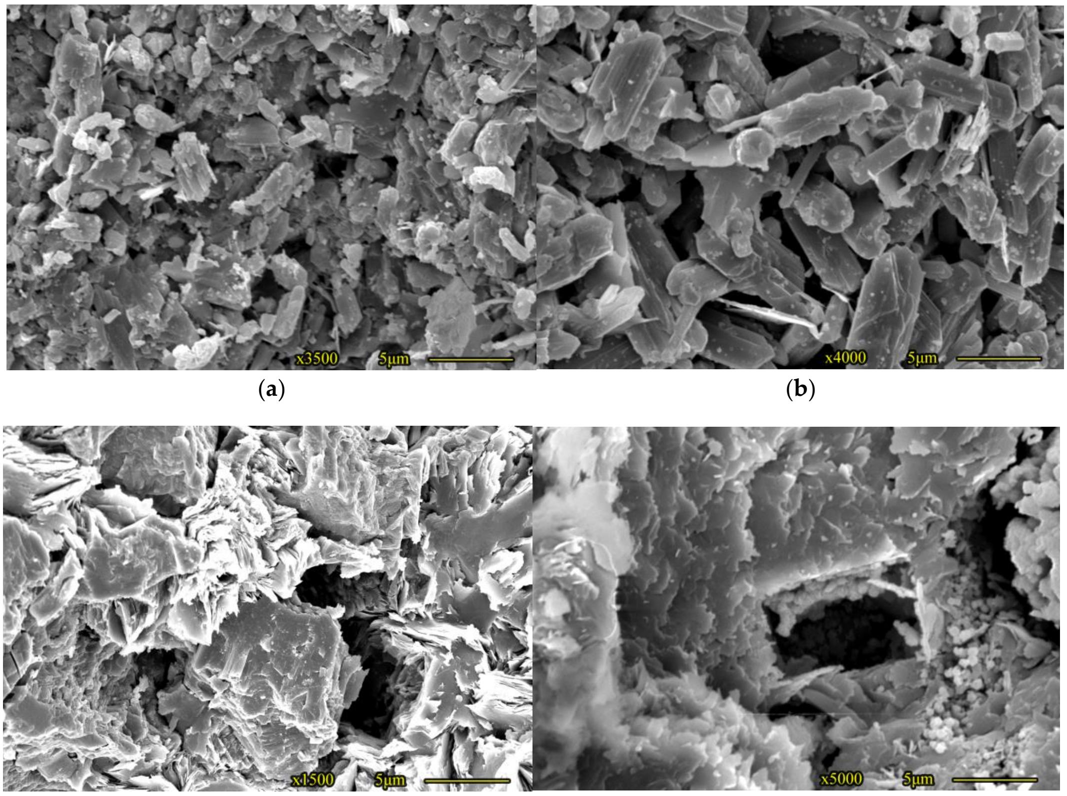


Figure 9. EDS analysis of bauxite. (**a**) EDS analysis of compact tabular diaspore. (**b**) EDS analysis of diaspore and anatase. (**c**) EDS analysis of scaly diaspore. (**d**) EDS analysis of fine sheet kaolin.

2.3.2. Physical Property and Pore Structure Characteristics of Ore Body

According to the test data of scanning electron microscope and pore permeability analysis of bauxite, the bauxite develops pores and fractures, and the reservoir has showed good physical properties. The porosity ranges from 1.3 to 6.1%, and the permeability varies from 0.042 to 5.25 mD.

Scanning electron microscopy showed that the bauxite and aluminum-soil mudstone were mainly characterized by intercrystalline pores of diaspore (maximum pore size up to 1.2 μm), intergranular and intrgranular dissolution pores, and microfractures (Figure 10).



(**a**) (**b**) (**c**) (**d**)

Figure 10. Characteristics of micro pore throat structure of bauxite. (**a**) Closely packed bauxite, semi-autogenous -autogenous pseudohexagonal sheet, bauxite intercrystalline pores 3500×. (**b**) Bauxite, semi-autogenous—autogenous false hexagonal sheet, bauxite intercrystalline pores 4000×. (**c**) Bauxite, mostly semi-self-shaped false hexagonal sheet or other shape, poor crystallization, bauxite intercrystal pores micro-cracks 1500×. (**d**) Amorphous silicon and aluminum colloidal particles, irregular, granular pores and intergranular pores 5000×.

The constant mercury injection into the high permeability reservoir section indicates a good pore connectivity, a drainage pressure between 0.21~0.42 MPa, and the maximum connected pore-throat radius between 1.81~5.22 μm. The median pressure is between 5.90 and 6.11 MPa, and the average throat radius is generally between 0.09 and 0.67 μm, which is a common characteristic of dissolved pore type reservoir.

2.4. Evaluation of the Deep Bauxite

In oil and gas exploration, well logging shows that the bauxite is developed at the bottom of Benxi Formation, and the buried depth is from several hundred meters to several thousand meters. Previously, this set of bauxite has been used as the marker of Benxi Formation and the underlying Majiagou Formation in stratigraphic correlation, and has been regarded as the regional cap of weathering crust gas reservoir in oil and gas explorations.

As a marker, the bauxite layer has obvious electrical characteristics, which are characterized by "four highs and two lows", namely high gamma, high thorium, high uranium content, and high compensating neutrons, and low resistance and low acoustic time difference. The GR is abnormally high. Due to the finer particles and larger specific surface of bauxite, it is easy to adsorb radioactive substances such as uranium, thorium and titanium. The natural gamma is positively correlated with the content of diaspore. When the bauxite content exceeds 75%, the GR ray content is greater than 450.0 API, therefore, natural NG mark is the most key of logging parameters for identification of bauxite. Dual lateral resistivity (LLD, LLM) is 35 Ω/m or so commonly, a maximum of 100 Ω/m. The resistivity corresponding to the high gamma interval generally decreases, and the positive difference between the log curves of the double lateral resistivity is obvious. Due to the high gamma section of high contents of bauxite, bauxite is crisp, easy to form micro fractures and solution pores, resulting in the decrease of resistivity [23].

The parameter characterization of bauxite layer is the basis of bauxite identification, evaluation and reserve calculation. On the basis of X-ray diffraction analysis of whole rock minerals, ore physical property measurement, scanning electron microscopy and other data, a parameter interpretation model of bauxite layer is established based on core scale. According to the mineral types of the classical rock volume model and the mineral analysis results of the whole rock by X-ray diffraction, the content of diaspore was determined by natural gamma ray and density fitting. The porosity model was established by intersection of core analysis porosity and acoustic time difference. According to the correlation between porosity and permeability, the permeability of bauxite layer was obtained by using porosity [24]. Finally, deep bauxite logging evaluation can be completed, and bauxite identification, evaluation and reserve estimation can be realized.

Special logs such as ECS, NMR, dipole acoustic and acoustic imaging can also be used to evaluate bauxite deposits. ECS element logging can obtain the content of formation elements and rock mineral composition, which can satisfy the evaluation of various properties of the formation, obtain the physical parameters of the formation, and calculate the content of clay minerals. Dipole acoustic logging can provide the time difference of longitudinal and shear waves, and can perform anisotropy analysis and processing to determine the direction of the maximum horizontal formation stress, calculate the maximum and minimum formation stress horizontally, and obtain the Poisson's ratio, Young's modulus, and shear modulus of the rock. All these important rock mechanical parameters are used to meet the requirements of establishing the calculation model of rock and guide the fracturing transformation. Acoustic and electric imaging logging has the characteristics as high resolution, high borehole coverage and good visibility, and it is of great significance to identify fracture types to guide reconstruction and evaluate development effects [25].

Based on the above results, the bauxite resources in the south of Ordos Basin are evaluated. The bauxite is widely distributed in the Ordos Basin, which has a good correlation with the Ordovician karst paleogeomorphology. The bauxite is controlled by the Ordovician microgeomorphology, distributed in strips and lenses, and has great exploration potential.

3. Conseptation of the In-Situ Leaching Mining Technique and the Applicable Conditions

3.1. Conception of In-Situ Mining of Deep Bauxite

In-situ leaching mining is the best way to effectively exploit the deep bauxite resources in the basin. The sedimentary stability, roof and floor conditions, orebody permeability and other aspects of bauxite in the Ordos Basin are well matched with in-situ leaching mining.

Bauxite is a sedimentary rock with certain porosity and permeability, and presents a sandwich structure, which is often surrounded between the top and bottom clay rocks. It has the geological conditions of in-situ leaching mining, especially according to the stress sensitivity tests, new pores or cracks will appear with the increase of stress in bauxite, which can improve the permeability of the ore layer. Based on the in-situ leaching mining technology of uranium ore and rare earth ore, the in-situ leaching mining of bauxite can be considered.

In-situ leaching mining uses a liquid injection well to inject specific leaching solution into the target orebody, leaching useful metals through a series of physical and chemical reactions, and pumping the leaching solution out of the surface through the pumping well to achieve the process of extraction of useful metals in the surface factory [26]. As shown in Figure 11, the main implementation steps of in-situ leaching mining of bauxite include:

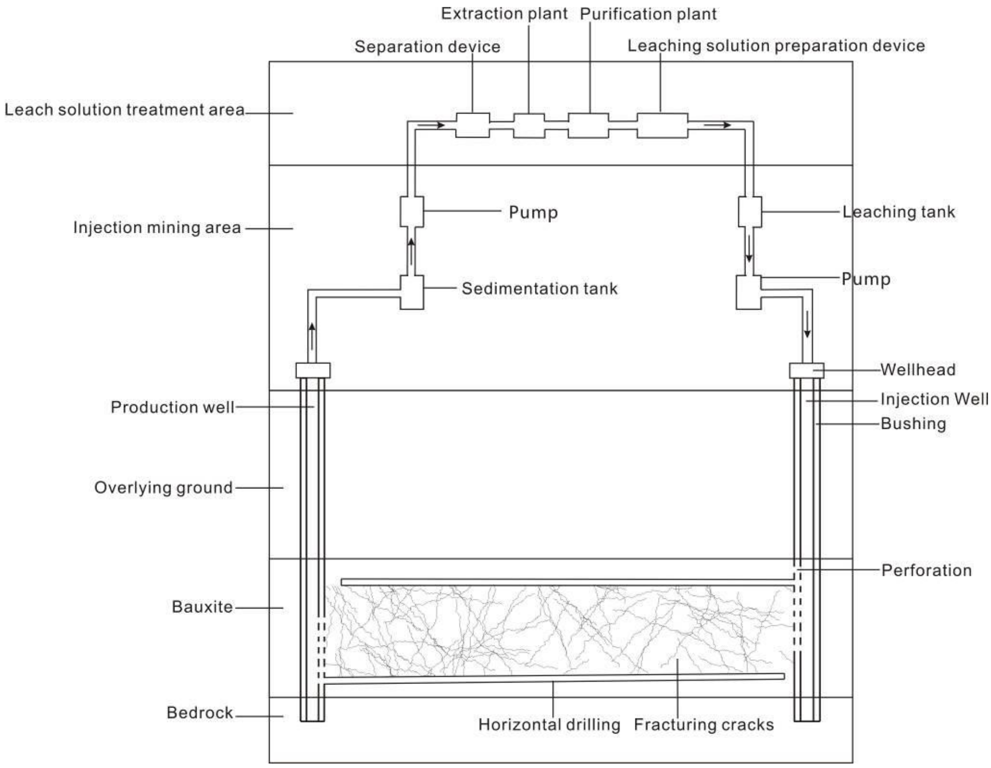


Figure 11. In-situ leaching of bauxite mining concept map.

(1) Drilling: cluster well are adopted, with the inverted nine-point method, the inverted seven-point method or the inverted five-point method to distribute the injection and production well pattern, including the liquid injection well and the drainage well. The liquid injection well is located in the middle position, and the drainage well is located in the surrounding position. The liquid injection well is a vertical well, and the drainage well is a directional well (as shown in Figure 12). The well was drilled through the overlying bauxite to 20 m of the underlying bauxite bedrock and completed with casing.

(2) Reconstruction of the ore layer: The perforation section is set at the top of the bauxite bed in the liquid injection well, and the drainage well is set at the bottom of the bauxite bed. The horizontal borehole is drilled on the top of the bauxite bed with the liquid injection well as the starting point and the drainage well as the ending point. The horizontal borehole extends horizontally from the liquid injection well to the drainage well parallel to the roof of the ore bed, where the first horizontal borehole is not connected with the drainage well. Then, a horizontal borehole is drilled at the bottom of the bauxite layer with the drainage well as the starting end and the liquid injection well as the end point. The inclination angle of the horizontal borehole from the drainage well to the liquid injection well is upward inclined. The horizontal drilling hole is not connected to the liquid injection well. The liquid injection well is fractured or blasted by hydraulic power to increase the permeability to form fracturing cracks in the bauxite layer and establish a seepage channel.

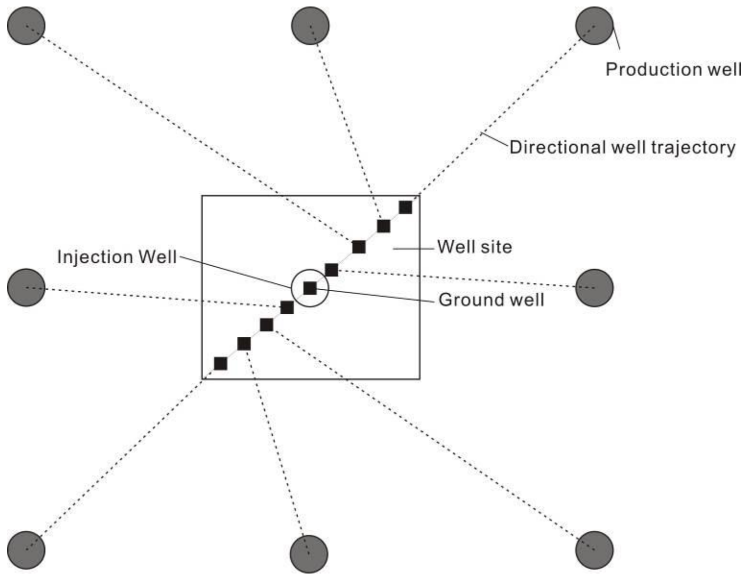


Figure 12. In situ leaching of bauxite mining well pattern diagram.

(3) Leaching operation: leaching solution is injected into the liquid injection well, and it enters the bauxite layer through the perforation section of the liquid injection well and the horizontal borehole at the top. The bauxite is dissolved through the downward seepage of the fracturing fracture, and then the dissolving liquid containing bauxite is extracted to the ground through the seepage of the horizontal borehole at the bottom and the perforation section of the drainage well.
(4) Ground operation: After settling the leaching solution containing bauxite, the leaching solution containing bauxite can be separated and extracted, and then reused after purification treatment.

3.2. Conditions for In-Situ Leaching of Deep Bauxite Deposits

In-situ leaching mining is a very special mining method, and its application conditions are very strict. Not all deposits can be mined by in-situ leaching, and those that can be mined may not be technically and economically feasible. Only bauxite with certain geological-hydrogeological conditions has the possibility of in-situ leaching technology for economic exploitation. The investigations show that the feasibility evaluation of in-situ leaching is a very important and difficult subject. Therefore, it is very important to study the selection of in-situ leaching mining for bauxite. The bauxite selection that can be in-situ leaching mining needs to solve the following problems: (1) whether it is permeable to ensure that the leaching solution can flow in the ore layer; (2) whether it is soluble, which can ensure the leaching rate, the content of beneficial minerals in the leaching solution and the consumption of leaching agent; (3) whether there is a closed top and bottom conditions, can ensure that the leaching solution does not leak, does not pollute the formation water, to ensure the recovery rate of leaching solution. On the basis of considering the above problems, the conditions of bauxite deposits suitable for in-situ leaching mining were sorted out (Table 1).

Table 1. Deposit conditions of in-situ leaching bauxite.

Category of Conditions	Parameter
Condition of geology	Lithology and lithofacies characteristics Degree of cementation and diagenesis of ore The mineral composition of an ore and its percentage Thickness of roof and floor Continuity of roof and floor Grade of ore Distribution characteristics of ore beds Thickness of ore bed The depth of the mine
Hydrogeological conditions	Reservoir permeability (experimental data) Reservoir effective porosity Roof and floor permeability Reservoir permeability (data from pumping tests) Top bottom aquifer
Ore leaching process conditions	Beneficially metal leaching rate of ore sample The leaching solution has beneficial mineral content Unit metal leach agent consumption Time required for leaching Cleaning process test ore sample to cleaning water consumption

4. Countermeasures for Water Pollution Control In Situ Mining of Deep Bauxite

Compared with traditional mining and open-pit mining, the in-situ leaching mining has achieved green and pollution-free mining to a large extent, but the complex and changeable underground ore bodies, surrounding rock, roof and floor, permeability and solubility of ore bodies are difficult to predict, and it is easy to form leaching agent leakage, which will not only reduce the efficiency of in-situ leaching mining, but also cause water pollution [27]. To prevent and control this potential problem, the seepage control strategy of deep orebody leaching solution is put forward, including polymer resin filling and well pattern seepage control.

4.1. Seal with Polymer Resin

Injection of polymer resin plugging refers to the injection of polymer resin insoluble in leaching agent into the top and bottom of the mineral layer before the injection of leaching agent, forming a polymer material barrier layer to prevent leaching solution through the top and bottom into the aquifer (Figure 13). According to the hydrogeology of Ordos Basin, the Carboniferous Benxi Formation bauxite layer is covered by Ordovician carbonate rocks, and its groundwater belongs to karst water, which is the main aquifer in the periphery of the basin. Therefore, the injection of polymer resin between bauxite layer and carbonate rock can effectively form plugging and prevent the pollution of karst water by leaching agent. Leakage points are identified through a combination of drilling, logging, geophysical exploration, and tracer water injection testing. Subsequently, polymer resin is injected into the borehole to seal these points and prevent the leakage of leaching solution into the aquifer.

4.2. Well Pattern Seepage Control and Plugging

Well pattern seepage control plugging refers to controlling the flow direction of the underground leaching solution by setting the well pattern to prevent the leaching agent from entering the aquifer (Figure 14). Radial horizontal holes are drilled at the top of the ore layer to inject the leaching solution, and radial horizontal holes are drilled at the bottom of the ore layer to drain the leaching solution. To prevent the leaching solution from running through the floor, multiple radial horizontal drilling holes can be drilled at the bottom of the ore layer in the drainage well to collect the leaching solution, and the flow direction of the leaching solution can be controlled by the pressure difference between the horizontal drilling hole of the injection well and the horizontal drilling hole of the drainage well to prevent leaching solution from leaking and contaminating karst water at the bottom of the ore layer.

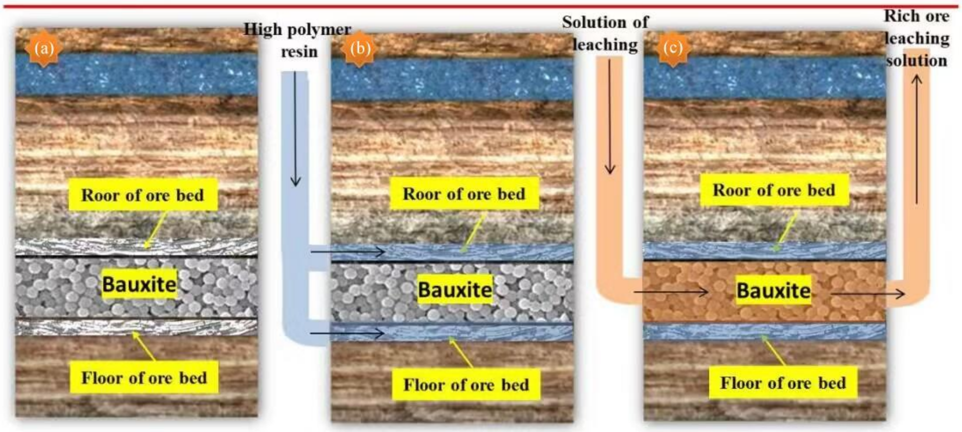


Figure 13. Schematic diagram of water pollution prevention with polymer resin infusion. (**a**) The stratigraphic procedure; (**b**) Schematic diagram of polymer resin filling; (**c**) In-Situ Leaching Mining after resin filling.

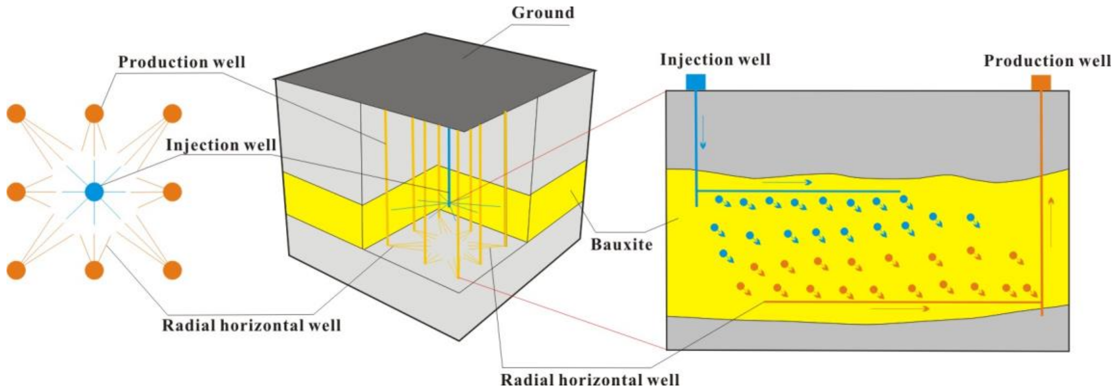


Figure 14. Schematic diagram of seepage control of well pattern to prevent water pollution.

4.3. Establish Production Dynamic Monitoring System

Based on the hydrogeological research of the mining area, the dynamic production monitoring system is designed to find out the geological conditions of the mining area, deploy monitoring wells around the leaching area, track the groundwater situation of the mining area in real time, investigate whether there are objects that need to be targeted for pollution prevention, treat environmental problems from the root, and build a dynamic production monitoring system [28]. The dynamic monitoring system includes the global underground seepage monitoring system, groundwater index monitoring system, and three-dimensional visualization system of leaching mining area, which can monitor and prevent potential problems in real time, and deal with the problems in time, so as to comprehensively prevent and control the occurrence of water pollution events.

5. Conclusions

(1) Geological research, including drilling and logging data, has revealed that the deep bauxite deposits in the Ordos Basin exhibit a sandwich structure. This structure is characterized by layers of claystone or shale above and below the bauxite deposit. Furthermore, analysis of the bauxite using techniques such as Scanning Electron Microscopy (SEM) and pore seepage analysis has shown that the bauxite contains pores and fractures, indicating favorable reservoir physical properties.

(2) The use of in-situ leaching mining technology in the extraction of metal solid minerals has certain prerequisites. Sedimentary bauxite ore exhibits inherent characteristics that make it suitable for this technology, including solubility, stability of ore body deposition, favorable top and bottom plate conditions, and permeability of the ore body. These characteristics provide a foundation for the application of in-situ solution leach mining to deep bauxite ore in the Ordos Basin, and the concept and steps for this mining method are proposed.
(3) This paper discusses how to establish barrier layer by means of well pattern seepage control and polymer resin infusion to prevent leaching solution from entering aquifer, and establish dynamic monitoring system in mining area to track and monitor groundwater situation in real time and prevent water pollution.

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