Hydrogeology and groundwater control at Chambishi mine, Zambia

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Abstract

The hydrogeological conditions in the Chambishi mine area in Zambia. were investigated. Chambishi is a very wet mine and groundwater discharge costs are high. The research goal was to identify methods to reduce the discharge costs without greatly affecting the mining process.

Hydrogeological data was obtained from measurements in drill-holes and from drill cores. The differences in structural deformation in different areas determine whether a layer of rock is an aquifer. In the mine region, the Lower Roan Group ore shale and quartz-sandstone unconformably lie on the basal schist and granite aquifuge. The Upper Roan Group dolomite is continuously distributed over a large area around the orebody. This dolomite is the main target of groundwater control efforts, and its water yield is also influenced by the deformation intensity.

Based on the observations, backfilling was gradually adopted to appropriately safeguard the integrity of the aquifuge above the orebody. The overlapping relationship between the aquifer and aquifuge has been utilized to increase mine drainage efficiency. This measure has not only greatly reduced the costs of mine drainage, but also improced protection of the groundwater environment. The old drill-holes that were not sealed after exploration drilling were grouted.

Further, possible water-conducting fracture zones were investigated. Cover drilling towards the suspected zone was conducted to prevent the high-pressure groundwater from shallower aquifers from entering stopes in deep areas of the mine.

Keywords

hydrogeology, aquifer, aquifuge, structural deformation, backfill

Introduction

We report the results of a hydrogeological investigation at the Chambishi copper mine in the Zambian Copperbelt. The aim of the investigation was to ascertain the deep level hydrogeological conditions and to ensure safe mining. The Chambishi copper mine is located along the northern–northeastern margin of the Chambishi structural basin. The mining concession covers the region extending from the Main West deposit in the west to the South East orebody in the east, A distance od about 5 km.

The Chambishi structural basin includes a large area of soluble rock aquifer. Thus, the mine area is rich in groundwater, and because of the high inflow of water, the discharge costs are high. The objective of this research was to identify technical measures to reduce drainage costs without affecting mining activities. We first present a brief description of the study area and the research topic. This is followed by detailed descriptions of the two deposits with regard to the aquifers and aquifuges, and a description of the water control measures. Finally, the main findings of this research. are summarized.

Background

The topographic relief in the mine area is gentle; the general terrain slope is 2–4%, and the local elevation difference does not exceed 50 m. This gentle relief and undulating landform are favourable for rainwater infiltration. The vegetation is well developed and comprises mainly shrubs and a dense grass cover. Hydrophilous plants flourish in the low-lying areas and on the sides of rivers and streams. The dense vegetation cover is also favourable for increasing the precipitation recharge to groundwater. The annual average rainfall is 1 181 mm, and the annual maximum and minimum are 1 659 mm and 630 mm, respectively. The maximum monthly rainfall is 489 mm, typically 20 mm to 40 mm at a time, and long duration large rainstorm are rare. This pattern of rainfall also favours the infiltration of rainwater.

The gentle topographic relief, dense vegetation cover, plentiful precipitation, and moderate rainfall intensity are all favourable for recharge to the groundwater. These conditions are important factors contributing to the groundwater in the mine area.

Main West deposit: Aquifer and aquifuge

The basal schist, quartzite, and granite intrusive form an extensive and continuous aquifuge surrounding the Chambishi basin. These lithologies contain limited fissure water only near some structural belts or in some parts locally affected by the paleo-weathering zone. Most of the mining development is located in these lithologies.

The ore-bearing Lower Roan Group is composed of conglomerate, sand-slate, and shale/schist, with interlaid sandstone and quartzite above the ore horizon, and some carbonate interlayer. This Group is usually an aquifer with low or moderate water content. However, its water content may increase with increasing increaseincreasinge in the foldfolding deformation. The interlayer slippage and folds within the ore shale are common structural phenomena, and they often form the transition zones and slips between different structural units. The total groundwater inflow from this layer may not be large. However, since most mining development is in this Group, it is classified as a major aquifer. Here, one factor to be emphasized is that an approximately 20 m thick Upper Quartzite layer is located immediately above the Lower Roan Group. This layer is hard and competent, and serves as a good aquifuge when it is not breached by fractures.

The Upper Roan Group is dominated by dolomite in the lower part and interbedded dolomite and shale in the upper part, with a total thickness of up to 700 m. The middle and lower parts of this sequence generally contain gypsum. Because of the solubility of gypsum, the porosity of the aquifer can reach 10% or more. The section of the Group where gypsum has dissolved forms the major aquifer in the mine, and dolomitic sands are often present in this section. Concordantly intruded gabbro sills of thickness from tens of metres to 200 m are distributed intermittently in the middle part of the Group. The sill may act as aquifuges, but because they are limited in area, they can only be considered as a local aquifuge.

The lithology of the Mwashia Group comprises carbonaceous shale and dolomite. The dolomite also constitutes an aquifer, which has a low to moderate water content. In some sections, caves are developed locally and these form strong aquifers.

The Kundelungu/Nguba Group comprises shale, limestone, and tillite conglomerate at the bottom. It is mainly distributed in the middle of the basin, covering other strata. Where the Group is thin, it forms a weathering fissure aquifer. Where the shale and moraine conglomerate are thicker, a relative aquifuge is formed.

The residuum and weathering zone aquifers have a general thickness of 20–60 m, but may be more than 100 m thick in places. Most of the aquifers have a weak water yield.

Main West deposit: Water control measures

The upper stratum above the ore shale in the Main orebody has undergone strong deformation, thereby increasing its permeability. Therefore, when mining in the Main orebody a large volume of water inflow is encountered. Most of the hangingwall of the Main orebody experiences has poor geotechnical characteristice, and stope hangingwall stability is not good. The folds above the ore shale in the shallow stratum are shown in Figure 1, and the representative profile of the Main orebody is shown in Figure 2.

The open pit was begun in 1965, and the underground mine became operational in 1974. ZCCM adopted sublevel caving as the underground mining method. In such situations, large-scale drainage must be established in advance. The drainage works were generally located 100 m lower than the mining level, and their construction commenced about one year before mining. The large volume of water inflow and poor stability of the orebody and wall rock resulted in very high mining costs. In 1987, the mine was shut down for maintenance. Later, in 1998, NFCA took over the mine. Subsequently, the hydrogeology, water control, and mining methods were thoroughly examined. Detailed studies revealed that the complex folding in the ore horizon and overlying strata in the shallow part of the mine changes to a relatively simple monocline in the deeper part. Very steep structures still exert great influence on the stratum conductivity. The high permeability and relatively high water temperature (40°C) may be associated with the reactivation of the Lufilian Arc or a more recent tectonic event (rifting). Above the ore horizon, the cherty dolomite in the Upper Roan Group, which is located about 70 m above the orebody, is the strongest aquifer. Furthermore, the upper quartzite, located 40 m above the ore horizon, constitutes a good aquifuge. From the time that mining operations were restarted, sublevel caving has bee used in some mining sections, with backfilling adopted in other parts.

Backfilling does not cause large-scale damage to of the hangingwall rock. It improves ore recovery and significantly reduces ore dilution. The Upper Quartzite can act as an aquifuge to prevent the large volume of groundwater from the cherty dolomite entering the stopes. The mine drainage works only aim to drain the ore horizon and the associated strata below the Upper Quartzite. Most of the drainage boreholes can be terminated at the Upper Quartzite and need not penetrate the cherty dolomite strong aquifer, as was done during mining by ZCCM. Thus, the drainage intensity requirements were reduced, and accordingly, the costs of mine drainage works, as well as the water discharge volume, decreased.

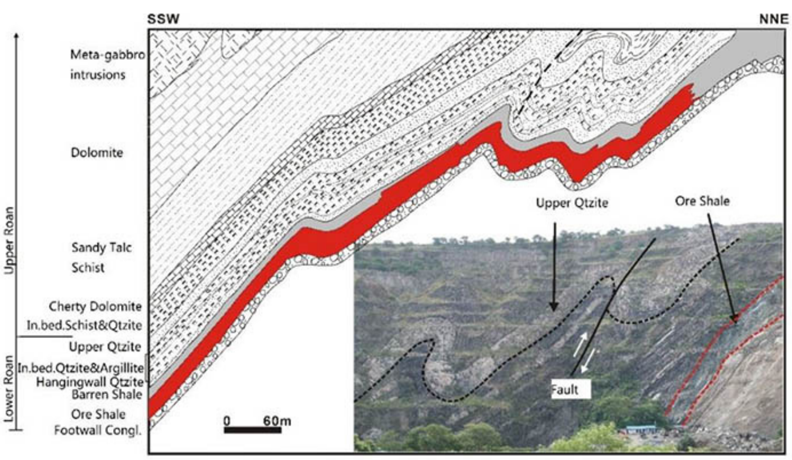

Figure 1— Folds in the shallow stratum of Chambishi Main orebody

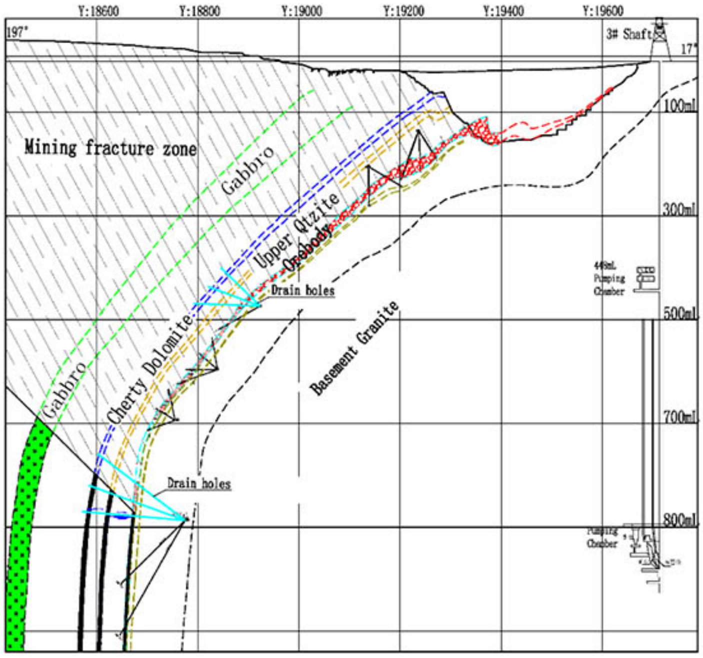

Figure 2—Schematic profile of Chambishi Main orebody (modified from Greyling et al., 2005)

The above measures helped restore production from the Main orebody in a relatively short time. Production continues at present. The depth of mining has reached the 732–865 m level from the 400–500 m level at the time production was restarted. The water inflow increased from 36 000 m^3/d to 47 000 m^3/d. Water from the sublevel caves, which constitute less than half of the total orebody length, accounts for two-thirds of the total water inflow, whereas the backfilling mining area accounts for only one-third.

The West orebody is adjacent to the Main orebody and has similar hydrogeological characteristics. Based on the experience gained from mining the Main orebody, backfilling mining was adopted in all sections in the West orebody. In addition, a more advanced technique – paste filling – was introduced to further improve the backfilling quality and to provide better protection for the hangingwall. Paste filling has the advantages in that it undergoes no separation, segregation, or dehydration, and is a more compact filling. The characteristics of the paste filing material and a comparison of filling strengths are shown in Figure 3.

The mining and drainage depth at the West orebody has reached the 500 m level. Although the mining area is almost as long as the Main orebody, the total water inflow is less than 10 000 m^3/d. The combination of selective drainage with backfill mining leads to satisfactory results. Through the use of advanced mining technology and a fine drainage works layout, the mine drainage cost has been greatly reduced, and the surrounding groundwater environment is well protected.

At present, the mining depth at the Main orebody is close to 900 m, and most of the proven resources have been depleted. Because of the large water inflow, mining of the remaining resources has become more difficult and higher costs are incurred. The adjacent West orebody has a relatively shallow mining depth and contributes the majority of production. While most of the water comes from the Main orebody, water inflow is considerable, and the drainage head is high. The drainage costs impose a heavy burden on production at the Main West orebody.

Southeast orebody

The Southeast orebody is located 5 km southeast of the Main West orebody. Here, the orebody is located at a great depth, and the surface hydrogeologial conditions are complex. Therefore, the mine was not developed until recently. The designed mining scale is 3.3 Mt/a. Mine construction commenced in 2013, and trial mining was conducted at the end of 2018. The distribution of the orebody and the surface water systems are shown in Figure 4.

The Mwambashi River flows from west to east through he Chambashi Basin and then joins the Kafue River. The drainage area of the river is 760 km^2, and average flow rate is 3.4–9.6 m^3/s with a maximum flow rate of 36.7 m^3/s.

Owing to the impact of the paleo-sedimentary environment, the Southeast orebody has an extensive distribution and a complex shape. The orebody is 7 km long and 500–800 m wide. There are two other small orebodies on its north side. The northern part of

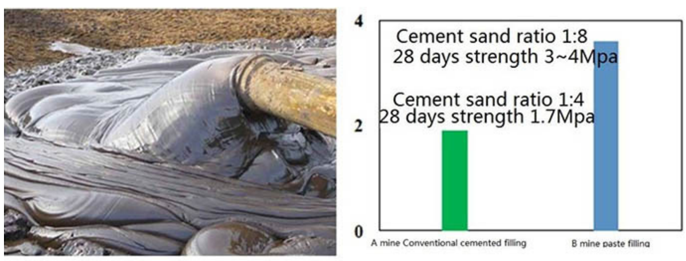

Figure 3— Paste filling material characteristics (left) and a comparison of filling strengths (right)

Figure 4 – Distribution of the Southeast orebody and surface water systems

the orebody is located in a relatively high terrain between rivers; surface water is not developed and rainwater drainage is good. The orebody is at a depth of 700–1 000 m in the northern part. Hence, the northern part (north of the zero exploration line – see Figure 4) has been chosen as the first-stage mining area, so as to minimize the impact of the rivers on mining. The southern part of the orebody is shallower, and the ore horizon is closer to the aquifer. The bioherm dolomite (Greyling et al., 2005) adjacent to the orebody may also behave as the main aquifer. The Mwambashi River and Ichimpe stream flow above this ore section. The river seepage may be responsible for recharging water to the ore horizon. This part of the orebody is reserved for later mining.

Southeast orebody: Aquifer and aquifuge

In the first-stage mining area, the strata can be clearly divided into the aquifer in the shallower part and the aquifuge in the deeper part. Both have similar thicknesses. The shallower aquifer includes the Mwashia dolomite and the upper part of the Upper Roan dolomite. The aquifuge includes the lower part of the Upper Roan, the Lower Roan, and basement. The gypsum-bearing arenite and the cherty dolomite, which is a strong aquifer in the Main-West orebody, form a part of the aquifuge in the Southeast orebody. The karst section of the upper portion of the Upper Roan dolomite is the strong section of the aquifer. Photographs of a core from the strong section of the aquifer are shown in Figure 5.

The brecciated dolomite of the Upper Roan and the entire Lower Roan are hard andcompetent; they form the aquifuge. Typical core is shown in Figure 6.

The basement Lufubu schist, quartzite, and gneissic granite form the footwall of the aquifuge, and also form the regional impervious boundary, outcropping at the northeast and east of the basin. The typical profile of the stratum attitude in the first-stage mining area and the aquifer-aquifuge distribution are shown in Figure 7.

Exploration and research work

NFCA conducted detailed exploration from 2008 to 2013. During this period, 83 boreholes totalling 68 844 m were drilled in the Southeast orebody. Of these, 15 were hydrological investigation holes. Hydrogeological logging was conducted for all 83 holes. Among these, 19 holes were used for monitoring the groundwater

Figure 5—Core from the strong aquifer in the Upper Roan

Figure 6 —Typical core of the aquifuge of the Lower Roan

regime, and 55 pumping tests and 25 hydro-chemical analyses have been done. Ground temperaturea were measured in 17 holes. Five holes were used for the geotechnical investigation prior to shaft sinking.

Results and discussion

The results of the pumping tests for each aquifer (belt) are listed in Table I.

The results show that compared with the strata permeability reflected by the water yield of the Main West orebody, the conductivity coefficient for the Southeast orebody aquifer is clearly low.

Structural hydrogeological analysis was performed for the Southeast orebody. The ore horizon in the first-stage mining area is relatively undeformed. Ore-bearing strata are continuous with good integrity. This region is, on the whole, an 'integral massive block', lacking a strong conducting zone caused by tectonic factors. The forming of this 'integral massive block' is related to the different type of basement rock here compared with that in the other areas. The basements at the Main orebody and the southern part of the Southeast orebody are mainly granite. In contrast, in the first-stage mining area, the basement is schist and quartzite of the Muva and Lufubu Supergoups. Compared to the schist, the granite is more resistant to deformation. Therefore, the surrounding cover layer has experienced different intensities of folding deformation.

The ore shale and most of the overlying strata in the north part of the Southeast orebody have a gentle attitude, with dip angles 0–15°. In this regard, this orebody differs clearly from the Main orebody, which dips steeply from the basement to the basin centre. The intensive folding of the Main orebody results in a highly conductive aquifer that extends more than 1 000 m below the surface. The gabbro intrusion exerts great influence on stratum conductivity in the Southeast orebody. The outer contact zone of the intrusion forms a strong aquifer. Where the gabbro intrusion is thin, it forms a part of the aquifer. The influence of the intrusion is observed only in the shallower portion of the covering stratum; the deeper part of the area has experienced only weak tectonic influence.

Table I

Results of the pumping tests

Aquifer (belt)	Test number	Conductivity coefficient (m/d)			Average thickness of test segment (m)
		Low	High	Weighted average	
Weathering zone	6	0.07	1.52	0.56	15.4
Mwashia	4	0.06	21.5	0.65	35.2
Upper Roan	9	0.02	0.20	0.15	61.6
Deep fissure zone	5	0.01	0.07	0.03	8.1

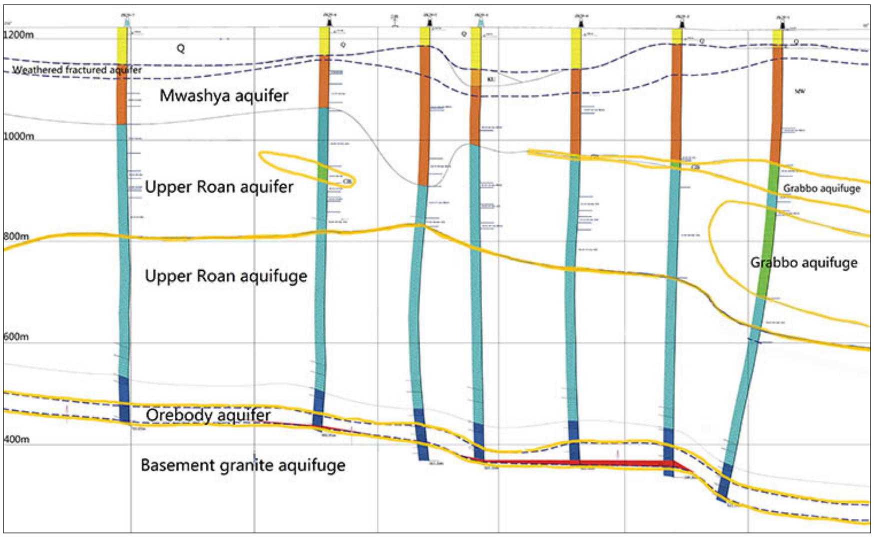

Figure 7— Typical profile of the strata attitude and aquifer-aquifuge distribution (Section 29)

The positions and thicknesses of the aquifers were determined from hydrogeological core logging and observations of all drill-holes. The thickness of the Mwashia limestone and dolomite aquifer is 50–100 m, while that of the Upper Roan aquifer (comprising dolomite and interbedded dolomitic mudstone) is 100–250 m. Between the aquifers is a relative aquifuge; a large part of which comprises a gabbro intrusion. A three-dimensional model of the spatial relationship of the aquifers with the orebody is shown in Figure 8.

The orebody, hangingwall, and footwall are all composed of hard rocks, with compressive strength Rc = 73.8–131.8 MPa and RQD = 95%. Good engineering geological features are favourable for maintaining the integrity of the stope hangingwall, thus preventing large inflows of groundwater from the upper aquifer from entering the mine.

At present, the development works and underground infill drilling have covered most of the first-stage mining area. Considering factors such as the overlapping of the aquifer and aquifuge, backfilling mining method, and actual water inflow in the existing developed works, the normal inflow of the first-stage mining area is predicted to be 10 000 m^3/d. However, considering the fact that the fissure zone and mining activities may cause leakage recharge of the shallow aquifer, the estimated maximum water inflow is 30 000 m^3/d.

Groundwater monitoring

The hydro-environment was studied thoroughly during exploration and construction of the mine, and a large number of hydrological observations were made. Observations during the exploration period show that the trend of the groundwater level is basically the same as that of the terrain in the Southeast orebody. This indicates that the large volume of drainage at the Main West orebody has no significant impact on the Southeast orebody, and the impact of mine drainage is limited. Observations during construction (from October 2012 to the end of 2016) showwd that in some holes, the water level gradually fell, but only by a few metres. The water flow in the developed mine originates mainly from the deeply buried water-conducting structure. The change in the water level is quite small, and this indicates that the hydraulic connection between the orebody and shallow aquifer is not distinct and that deep water inflow has limited impact on the surface.

Ground temperatures measured in drill-holes reached up to 38°C in the deep part of the mine, adversely affecting the mining work. In some holes at depths less than 400 m, the ground temperature is clearly lower than at other holes at similar elevation. This indicates that the groundwater infiltrates from the shallow to the deeper section. At depths greater than 400 m, the measurements tend to be consistent, indicating that the groundwater flow is very weak at the deep level.

The temperature of the water flowing from some infill drill-holes is 35°C or higher, with total dissolved solids of 2 007–2 426 mg/l. The pumping tests show that water from the deep segments have TDS 1.02–1.34 g/l. The groundwater conductivity in the shallow aquifer is generally EC 500–1 200 µs, TDS 0.45–0.87 g/l, and that of Mwambashi River water is EC 400–800 µs, with total dissolved solids 0.51 g/l. These results show that the water flow from

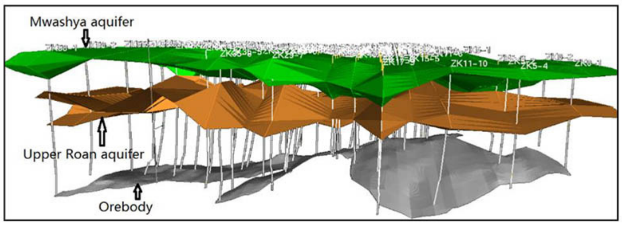

Figure 8—Spatial relationship between the aquifers and orebody in the first-stage mining area

the mining levels is only associated with the deep water-conducting structures and is not directly connected to the shallow aquifer.

Water control measures

Water control during shaft sinking

Four shafts were developed in the mine. The general water inflow rate for the shaft in the weathering zone aquifer is less than 10 m^3/h. The largest water inflow is located at a depth of 36.9 m in the northern ventilation shaft, with a flow rate of 39.2 m^3/h.

The dolomite aquifer located at a depth less than 200 m is the main source of water inflow. The water control method adopted here is advance water detection drilling with cement grouting at the shaft sinking face. The maximum flow rate encountered by detection holes reaches 200–300 m^3/h, with an average of 50 m^3/h. The water-detection holes in some shaft segments emit dolomitic sand and encounter interbedded soft and hard rock, as well as rocks rich in gypsum and talc. In the main shaft, it took half a year to control water by grouting at the sinking face, and 1500 t of cement was consumed before the shaft passed through the aquifer. Retrospectively, we think that pre-grouting at the surface before shaft sinking may be a better choice for these hydrogeologic conditions.

In the downward excavation process at the 560–680 m level ramp at the southern ventilation shaft, water enters from the blast-holes at the working face. Here, 20 t of cement was consumed for grouting. It was difficult to inject the grout fluid into the strata. After the ramp made a detour at some 10 m, the excavation was continued without encountering any more water.

Mining and backfilling

During the mining process, it is important to prevent large areas of damage to stope hangingwalls and to ensure close contact between the backfill and hangingwall. Paste backfilling should be utilized in the stopes of the thicker orebody. Hangingwall support is an important measure to reduce the water inflow and to delay the increase in water inflow.

Fault zones are the main factor leading to the deterioration of stope stability. In areas where fault zones are present, the stope dimensions should be adjusted according to changes in geotechnical conditions so as to improve the stability of the hangingwall.

Detection of fault/fissure zones

According to current understanding, the first-stage mining area is an integral massive block bounded by folds or fractures. Despite the flat-lying strata, slight tectonic deformation, and weak water content, analysis of the regional tectonic environment shows that folds or fracture structures may be present on the southeast and northeast sides of this area. These may be the boundary fractures (or folds) for the integral massive block. These two areas should be the focus of advance water detection work in the later mining stages

For the advance water detection drilling of such faults and fissure zones, the directional relationship between the drill-hole and the fissure zone should be taken into consideration. Better results can be achieved if the detection hole intersects the fissure zone at a high angle.

Treatment of old drill-holes

During the ZCCM exploration period, drill-holes were generally not sealed after completion. For a mine such as the Southeast orebody that does not contain much drainage ground water, such old drill-holes may constitute connection to the shallow aquifer. Therefore, the old drill-holes were opened up and re-sealed. Because of the restrictions on land use rights, some of the old drill-holes could not be sealed. When feasible, these holes should be sealed as early as possible.

Conclusions

- ➤ Low topographic relief, dense vegetation cover, plentiful precipitation, and moderate rainfall intensity are all favourable for recharge to the groundwater. These conditions are responsible for the abundant groundwater in the mine area.
- ➤ The major lithologies in the ore shale are dolomite or dolomitic siltstone. Under the effects of long-term weathering and leaching, an extensive and continuous aquifer with a high porosity has formed, with a large static water storage capacity. This makes the development and early drainage of a new mine very difficult.
- ➤ Intensive strata deformation promotes the dissolution of carbonate rocks, thus forming a strong aquifer. Clastic rocks with a low water content such as shale, calcareous sandstone, siltstone, and feldspathic quartzite also form aquifers when deformed. Folding intensity has a great effect on the regional planar water conductivity of an aquifer. Faulting plays a role in connecting the strata, forming a strong conductivity zone.
- ➤ The areal distribution of the aquifer is a determining factor for the total water inflow of a mine. There is a greater chance for a larger aquifer to be intersected by river systems, which provide a perennial recharge source.
- ➤ With increasing mining depth, the groundwater has a more obvious impact on mine development and mining costs. The groundwater distribution should be investigated in detail during the exploration and design phases. Drainage design should take into account the spatial relationship between the aquifers and aquifuge in order to arrive at a reasonable drainage design, minimizing the drainage costs.

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