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Application and prospects of block caving mining technology in China

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Abstract

Block caving mining is a large-scale, low-cost underground mining technology that has been in use for over a hundred years. Since China began adopting block caving mining technology in the 1980s, three block caving mines have been built and are in operation (Tongkuangyu mine, Pulang copper mine, and the western section of Yanqianshan iron ore mine), three mines are under construction (Panjiatian iron ore mine, Haoyao'erhudong gold mine and Yandong copper mine), and several others are in the preliminary research and approval stages. China now has a relatively high number of block caving mining applications. This paper systematically introduces the basic information of block caving mines in operation, under construction, or planned in China, as well as related technological research achievements in block caving mining. In the context of China's mining industry development, it analyses the challenges and opportunities for promoting the application of block caving mining technology in low-grade, thick deposits of copper, iron and other minerals in China, along with the urgent research directions that require further in-depth study.

Keywords: *block caving method, low-grade, thick ore deposits, mass mining, copper mine, open pit to underground transition*

1 Introduction

The block caving mining technique originated from the Pewabic iron ore mine in the United States and has a history of 130 years. Block caving is a high-technology, large-scale underground mining method. It involves undercutting blasting at the bottom of the orebody or at the base of a specific level, allowing the overlying ore to naturally cave in under its own weight and horizontal tectonic stresses, which extend the primary fractures. The caved ore is then transported through drawpoints at the bottom structure. This method is characterised by low cost, high efficiency and strong safety performance in mass underground mining operations (Laubscher 1994).

The block caving mining technique was introduced to China in the 1960s (Zhu et al. 2019). During this period and until the late 1980s, application trials were successively conducted in mines such as the Shizishan copper mine in Yunnan, the Jinshandian iron ore mine in Hubei, the Chengchao iron ore mine and the Fengshan copper mine, with successful implementation achieved at Tongkuangyu mine in Shanxi province. Currently, the block caving mines in production in China are the Tongkuangyu mine, Pulang copper mine and the western section of Yanqianshan iron ore mine. Additionally, several mines are under construction or in the planning stage, such as Panjiatian iron ore mine, Haoyao'erhudong gold mine, Shuangjianzishan silver-lead-zinc mine, Tongshan copper mine and Yechangping molybdenum mine. China has emerged as a global leader in the application of block caving mining technology.

China is a major consumer of mineral resources. The grade of domestic copper, iron ore and other mineral resources is generally low, making backfill mining uneconomic. Therefore, large-scale, low-cost, block caving

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mining technology has become the preferred method for developing large, low-grade, thick deposits. To promote the application and development of block caving technology in China, numerous scientific and technical researchers in the domestic mining sector have carried out extensive studies. Representative research institutions include China ENFI Engineering Corporation, BGRIMM Technology Group, Changsha Institute of Mining Research Co., Ltd., Central South University, University of Science and Technology Beijing, Northeastern University and Kunming University of Science and Technology.

This paper systematically summarises the application cases of block caving mining technology in China, analyses the current research status in the field of block caving mining and proposes development directions for this technology within China. The aim is to showcase the achievements of the Chinese mining industry in the field of block caving mining and to promote its further development in China.

2 Major block caving mines in production or under construction in China

There are nine block caving mines in operation, under construction or planned in China. Block caving mines in China are mainly distributed in the Shanxi, Yunnan, Inner Mongolia, Xinjiang, Henan, Liaoning, Heilongjiang and Sichuan provinces. The minerals extracted are primarily copper, iron ore, molybdenum, gold and silver, with a maximum annual production rate of approximately 12.5 million tonnes.

2.1 Tongkuangyu mine

2.1.1 Overview of the mine

Tongkuangyu mine is the first mine in China where block caving mining technology was successfully applied. Located in Yuncheng city, Shanxi province, it has been using block caving method since its introduction in the 1980s. The first phase of the project at Tongkuangyu mine, which involved the Lift 810 m, commenced production in October 1989, using slushers for ore extraction. The annual production rate was approximately 3.5 million tonnes. As mining progressed to greater depths and the first phase (Lift 810 m and Lift 690 m) was completed, construction of the second phase began in 2008, targeting the orebody between 690 and 410 mamsl (metres above mean sea level), divided into Lift 530 m and Lift 410 m. Undercutting blasting for the second phase started in June 2010, with a designed annual production rate of approximately 6 million tonnes. Currently, the mine has entered the extraction phase at Lift 410 m of the second phase, and the annual production rate has increased to approximately 9 million tonnes. According to the mine’s long-term plan, the design for deep-level mining is currently underway, and construction of the deep section is expected to begin in 2027.

2.1.2 Orebody characteristics

Tongkuangyu mine hosts two main orebodies (No. 4 and No. 5), which exhibit a large lenticular shape in plan view and a tabular form along the dip direction. The orebodies have an average thickness of 95 m, a strike extension of approximately 1,000 m, and an average grade of 0.61%, accounting for over 90% of the total reserves. The orebodies are primarily hosted within metamorphosed potassic basic volcanic rocks, with ore-bearing lithologies mainly consisting of metamorphosed quartz crystal tuff and metamorphosed quartz porphyry. The occurrence of the orebodies is generally consistent with that of the surrounding rock, striking northwest and dipping at angles ranging from 40° to 60°. The two orebodies are parallel to each other, with a relatively stable spacing of 110–130 m.

2.1.3 Mining method

The second phase project of Tongkuangyu mine adopts a development system combining a belt incline, auxiliary ramp and blind mixed shaft, with the ore pass and crushing system located at the 340 mamsl level. Currently, the main production levels at Lift 410 m include the 410 mamsl ore haulage level, the 434 mamsl extraction level, the 447 mamsl undercut level and the 442 mamsl return air level. The drawpoints at the extraction level are arranged in an offset herringbone layout, with a spacing of 15 m × 15 m. Large, cable reel electric LHDs (load-haul-dump machines) are used for ore extraction, with a load capacity of 10 t and a bucket capacity of 5.6 m³. The undercut height is 12 m, and undercutting is carried out using production drill jumbo, with undercut drifts spaced at 14 m and 16 m. Figure 1 shows the plan view of orebodies and layout of the 434 mamsl extraction level of Lift 410 m in Tongkuangyu mine.

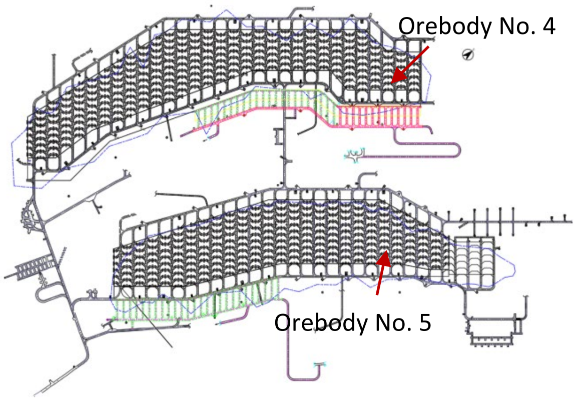


Figure 1 Plan view of orebodies and layout of the 434 mamsl extraction level in Tongkuangyu mine

2.2 Pulang copper mine

2.2.1 Overview of the mine

The Pulang copper mine is located in the northeastern part of Shangri-La city, Diqing Tibetan Autonomous Prefecture, Yunnan province, 72 km from the city centre. With elevations ranging from 3,450 to 4,500 mamsl, the mine operates under harsh production and living conditions. The Pulang copper mine has a designed annual production rate of 12.5 million tonnes. Construction began in April 2015, trial production started in March 2017, mass production commenced in August 2018, and full capacity was achieved in 2023. As the second block caving mine in China, the Pulang copper mine has become China's largest underground copper mine in terms of production rate.

2.2.2 Orebody characteristics

The mining area is located on the southern edge of the Pulang-Hongshan copper polymetallic sub-belt. The deposit formed within a composite porphyry body, with sulphide ore being the dominant ore type. The mineralisation zone extends over 2,300 m in length, with a width of 600–800 m, covering an area of about 1.09 km², and exhibits a domal shape. The main orebody, KT1, outcrops at elevations between 3,868 and 4,030 mamsl, with a maximum thickness of 495 m and an average thickness of 163 m. The orebody is primarily copper bearing, with associated gold, silver, molybdenum and other components, and has an average copper grade of 0.44%. The orebody strikes northwest, dips northeast at angles ranging from 35° to 70°, with an overall dip of approximately 65°. Mineralisation is continuous in the central part of the orebody, with splitting towards the periphery. The lithology structure in the mining area is relatively simple, consisting mainly of massive rocks. The rock is predominantly hard, with locally developed fracture zones where the rock is relatively broken.

2.2.3 Mining method

Figure 2 shows the longitudinal projection of development system at the Pulang copper mine. The first phase mining targets the orebody above the 3,720 mamsl. The maximum caving column of the orebody is 370 m, with an average caving height of 200 m. The first phase extraction involves four main production levels: from bottom to top, these are the 3,660 mamsl ore haulage level, the 3,700 mamsl return air level, the 3,720 mamsl extraction level and the 3,736 mamsl undercut level. An advancing undercut method is adopted, with undercutting direction arranged in a diamond pattern perpendicular to the orebody strike, advancing continuously from the centre towards the four directions of the diamond. The undercut drifts are located above the adjacent extraction drifts, with an undercut height of 15 m and drift spacings of 13 and 17 m. The bottom structure is arranged in an offset herringbone layout. Extraction drifts are spaced 30 m apart perpendicular to the orebody strike, with drawpoint drifts spaced 15 m apart and intersecting the extraction drifts at an angle of 50°. Based on the 45° angle principle, the undercut advancing line generally precedes the drawbell excavation 30 m ahead and the production working face 50–60 m ahead. Depending on the width of the footprint, one or two ore passes is/are arranged in each extraction drift. Ore is dropped from the district ore passes to the 3,660 mamsl rail haulage level, where it is transferred via vibrating feeders into mine cars. A 65 t electric locomotive hauls a train of 11 bottom-dump mine cars with a capacity of 20 m³ each, transporting the ore through the haulage drift to the dumping station. After crushing, the ore is discharged through the finished ore pass to the 3,540 mamsl belt conveyor adit and then transferred downhill via belt conveyor to the concentrator.

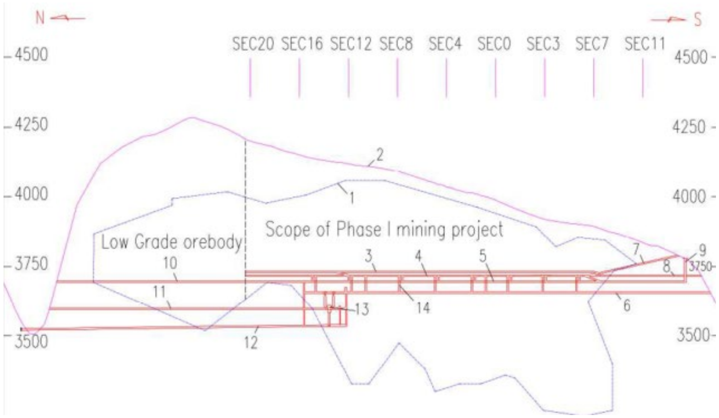


Figure 2 Longitudinal projection of development system at Pulang copper mine (Liu et al. 2020)

2.3 West section of Yanqianshan iron ore mine

2.3.1 Overview of the mine

The Yanqianshan iron ore mine is located in Anshan city, Liaoning province. Construction began in 1963, and the mine was put into operation in 1965. In its early stage, it was mined using open pit methods, with a designed annual production rate of 3 million tonnes. Open pit mining ended in 2012, resulting in an open pit bench measuring 1,410 m in length, 570–710 m in width, with a closure elevation of 93 mamsl and a pit bottom elevation of −183 mamsl. Subsequently, the mine transitioned to underground mining using the sublevel caving method, with a designed annual production rate of approximately 8 million tonnes. For the western section of the mine west of the F19 fault, a block caving mining design was adopted, with a designed annual production rate of 4 million tonnes, which has now been put into production.

2.3.2 Orebody characteristics

The Yanqianshan iron deposit is a large-scale sedimentary metamorphic iron deposit, consisting of three orebodies: Fe1, Fe2 and Fe3. The Fe1 orebody is the largest in scale with a consistent thickness. The Fe1 orebody occurs in the middle part of the Anshan group, with thin-layer phyllite and migmatite beneath it and phyllite along with the thin-layer Fe2 and Fe3 orebodies above it. Overall, it exhibits an upright monoclinic structure and is primarily composed of magnetite quartzite-type iron ore, intercalated with various schists, dykes and a small amount of high-grade iron ore. The three orebodies are distributed parallel to one another, each displaying an upright monoclinic structure, striking 270°–300°, dipping northeast, generally at angles of 70°–90°. The Fe1 orebody has a length of 1,747 m and a thickness ranging from 75 to 225 m; the Fe2 orebody is 364 m long with a thickness of 5–14 m, and the Fe3 orebody is 1,020 m long with a thickness of 21–415 m (Ma et al. 2008). The block caving mining area covers the western section (west of the F19 fault) at elevations between −321 and −15 mamsl. The average grade of magnetite is 29.55% TFe (total iron), of hematite is 27.98% TFe, and of carbonate iron ore is 28.38% TFe.

2.3.3 Mining method

The block caving mining operation in the western section of the Yanqianshan iron ore mine comprises four working levels. Among these, the −285 mamsl extraction level also serves as the return air level. In the western section, the maximum caving height of the orebody at Lift −285 m is 218 m, with an average caving height of 189 m. The extraction drifts in the western section are arranged approximately perpendicular to the strike of the orebody, spaced at 28 m intervals, with drawpoint drifts spaced at 14 m intervals. The drawpoints are arranged in an offset herringbone layout, with the drawpoint drifts intersecting the extraction drifts at an angle of 54°. The drawbell is 13 m long and 16 m high, with a bottom width of 3.8 m and a top width of 14 m. The extraction drifts and the drawpoint drifts both have a clear cross-section of 3.8 m × 3.7 m (width × height).

The undercut drifts are arranged perpendicular to the orebody strike and are positioned on both shoulders of the major apex pillars. The spacing between the undercut drifts is 13 m and 15 m (15 m on both sides of the major apex pillars and 13 m on both sides of the drawpoint funnels), with a clear cross-section of 3.8 m × 3.8 m. The cutting drifts are arranged along the strike on the hanging wall of the orebody, also with a clear cross-section of 3.8 m × 3.8 m. A cut raise is set every 10 m within the cutting drifts, with each cut raise measuring 2.0 m × 2.0 m in cross-section and 12.5 m in height. The overall undercut sequence in the western section advances diagonally from the northwest corner towards the southeast corner.

2.4 Panjiatian iron ore mine

2.4.1 Overview of the mine

The Panjiatian iron ore mine is located in Panzhihua city, Sichuan province, in a mountainous area. The highest elevation in the mining area is 2,607 mamsl and the lowest is 1,283 mamsl, giving a relative height difference of 1,324 m. It is a typical vanadium-titanium magnetite mine in the Panxi region. Open pit mining began in 1995, forming a pit that is below the surrounding terrain. Through multiple capacity expansions, the annual production rate gradually increased from 1.7 million tonnes in the early stage of mine construction to 6 million tonnes. The designed final elevation for open pit mining is 1,510 mamsl, with a closure elevation of 1,750 mamsl. Open pit mining is expected to end in 2029, at which point the mine will transition to underground block caving mining. The designed annual production rate for underground mining phase following the transition is 6 million tonnes, with a mine service life of 39 years (excluding the construction period).

2.4.2 Orebody characteristics

The Panjiatian deposit is a late-stage magmatic differentiated stratiform deposit. The natural ore types currently found in the mining area are simple, consisting of vanadium-titanium magnetite ore. Based on TFe grade, it can be classified into industrial-grade iron ore (TFe ≥ 20%) and low-grade iron ore (15% ≤ TFe < 20%). The orebody strikes nearly east–west, dips to the south, with a dip angle of approximately 40°. Within the mining area, the surface exposure of the orebody extends approximately 700 m along strike and 400 m in width from north to south, with a thicker central section that gradually pinches out towards the east. The low-grade orebody (Orebody No. 1) occurs within the gabbro lithofacies zone, while the industrial-grade orebody (Orebody No. 2) occurs within the pyroxenite lithofacies zone. Both orebodies are cut by the F1 fault in the central area, dividing them into eastern and western parts. Orebody No. 1 is located at the bottom of the gabbro ore-bearing layer, with its ore-bearing parent rock being gabbro. Its immediate roof is gabbro, and its immediate floor is pyroxenite or pyroxenite-type iron ore. Orebody No. 2 occurs within the pyroxenite ore-bearing layer, with its immediate roof being gabbro or gabbro-type iron ore, and its immediate floor being pyroxenite, locally consisting of metamorphic rocks of the Annincun Formation (plagioclase amphibolite). The low-grade orebody (Orebody No. 1) has an average thickness of 33 m, with a maximum thickness of 53 m and a minimum thickness of 14 m. The industrial-grade orebody (Orebody No. 2) has an average true thickness of 43 m, with a maximum thickness of 89 m and a minimum thickness of 10 m.

2.4.3 Mining method

In the Panjiatian iron ore mine, the orebody west of F1 fault will be primarily mined using the block caving method; other orebodies west of F1 fault and those east of F1 fault will mainly be mined using the sublevel caving method. Figure 3 shows a longitudinal section of the development system. The mine is developed in three lifts: Lift 1,320 m is the first development lift, followed by production lifts Lift 1,120 m and Lift 1,025 m. The mining sequence follows a top-down approach. After open pit mining ends, the operation transitions to underground mining. The 1,320 mamsl level serves as the first mining lift for the block caving area, and the 1,564 mamsl level serves as the first mining lift for the sublevel caving area.

Lift 1,320 m at the Panjiatian iron ore mine is divided into three main levels and seven sublevels, with a vertical spacing of 36 m between main and sublevels. Each main level consists of four key horizons: the extraction level, intake air level, return air level and undercut level. At the extraction level, 14 t electric LHDs (load-haul-dump machines) transport ore to ore passes, from which the ore is dropped to the rail haulage level. Each sublevel comprises three key horizons: the extraction level, return air level and undercut level, with ore also extracted using 14 t electric LHDs and transferred via ore passes to the rail haulage level.

At the extraction level, extraction drifts are arranged perpendicular to the orebody strike at 30 m intervals, with drawpoint drifts spaced at 15 m intervals. The drawpoints are arranged in an offset herringbone layout, with drawpoint drifts intersecting the extraction drifts at an angle of 50°. The spacing between undercut drifts is 15 m. Undercutting is carried out using a Simba 1354 production drill jamb to drill fan-shaped medium-depth holes.

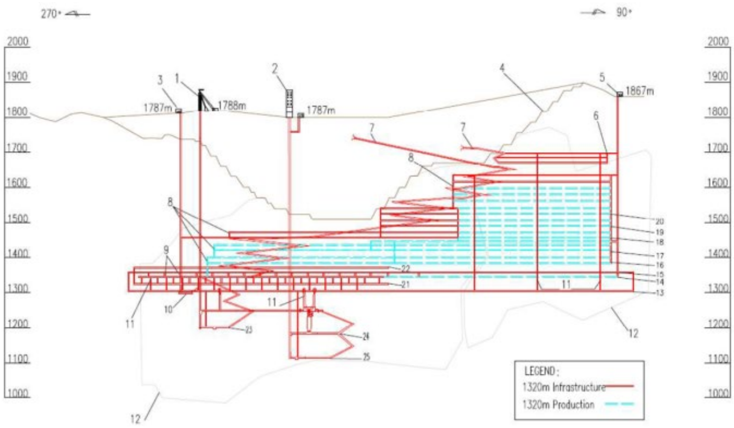


Figure 3 Longitudinal section of development system at Panjiatian iron ore mine (Liu et al. 2024)

2.5 Haoyao'erhudong gold mine

2.5.1 Overview of the mine

The Haoyao’erhudong gold mine is located 60 km from Urad Middle Banner in Bayannur City, Inner Mongolia Autonomous Region. The F2 fault divides the Haoyao’erhudong mine into eastern and western mining sections, both of which were initially mined using open pit methods. The western pit was mined down to the lowest elevation of 1,485 mamsl before being closed. The eastern pit is currently being mined down to an elevation of 1,234 mamsl, with open pit mining scheduled to end in 2028. The transition from open pit to underground mining will adopt the block caving method, with an annual production rate of 8.25 million tonnes and a service life of 22 years.

2.5.2 Orebody characteristics

The Haoyao’erhudong gold mine contains 36 orebodies: 16 in the eastern mining section and 20 in the western mining section. The main orebodies are E1 and W3. The orebodies strike 50°–64°, dip northwest, with dip angles of 65°–90°. The E1 orebody extends 1,918 m along the strike and has a dip extent of 1,023 m. The orebodies are tabular to sub-tabular in form with relatively simple shapes, remaining relatively stable along both strike and dip, with localised expansion and contraction. The proven resources of the main orebodies account for 79.44% of the total proven resources, and the gold metal content accounts for 81.37% of the total proven metal content. The ore industrial type is low-sulphide, quartz-veinlet altered rock-type gold ore, with an average grade of 0.68 g/t Au. The lithology of the orebodies and surrounding rock within the mining area is essentially the same, consisting mainly of low-grade metamorphic rocks such as slate, phyllite and schist.

2.5.3 Mining method

The transition from open pit to underground mining using the block caving method at Haoyao'erhudong is designed in two phases. The mine is equipped with an access ramp connecting the undercut level and the extraction level to facilitate the movement of personnel, materials and equipment. Extraction drifts are arranged perpendicular to the orebody strike at 30 m intervals, with drawpoint drifts spaced at 15 m intervals. The drawpoints are arranged in an offset herringbone layout, with drawpoint drifts intersecting the extraction drifts at an angle of 54°. The drawbell drift and extraction drift are arranged in a splayed pattern to ensure that the drawbell trench is parallel to the undercut longhole fan, which helps guarantee the blasting quality of the drawbell trench. External haulage drifts are located on both the hanging wall and footwall of the orebody. District ore passes are positioned near the external haulage drifts and are responsible for transferring ore from the undercut level (supplementary ore) and the extraction level to the rail haulage level. The undercut level is situated 16 m above the extraction level, and an access ramp is provided in the footwall external area to connect with the extraction level. Undercutting is carried out using an inclined undercut method with medium-depth holes. Two parallel undercut drifts are arranged on both shoulders of the major apex pillars above the extraction drifts, with a maximum undercut height of 15 m. The spacing between the undercut drifts is 13 m and 17 m. The entire mine adopts an advancing undercut strategy.

2.6 Yandong copper mine

2.6.1 Overview of the mine

The Yandong copper mine is located approximately 120 km southwest of Hami City, Xinjiang. The mining area lies on the southern edge of the Turpan-Hami Basin, with undulating terrain, a maximum elevation of +779 mamsl, a minimum elevation of +550 mamsl, and a relatively small elevation difference, characteristic of a low-mountain and hilly landform. The overall landscape surrounding the mining area is similar to a desert. The mining area experiences scarce rainfall, arid conditions and water scarcity, with no perennial surface water bodies or rivers. Temporary surface run-off generated by rainfall flows along dendritic gullies into intermountain depressions or valleys, where most of it is lost through evaporation, with only a small amount infiltrating underground. The Yandong copper mine is a newly developed mine. The mine design adopts a phased mining approach, with open pit mining in Phase I and underground block caving mining in Phase II. The designed annual production rate is 5 million tonnes, with a total service life of 48 years.

2.6.2 Orebody characteristics

The strata exposed in the Yandong copper mine area include the Carboniferous Queshan Group (C_1–$_2Q$), the Jurassic Xishanyao Formation (J_2x) and the Quaternary System (Q). The Yandong copper deposit occurs within the Carboniferous plagiogranite porphyry and its contact zone with the first lithologic member of the second formation of the Carboniferous Queshan Group. The orebody occurrence is generally consistent with that of the plagiogranite porphyry and the surrounding rock, clearly controlled by the emplacement of the intrusion. The orebody is mainly hosted in plagiogranite porphyry, with additional distribution in the surrounding andesite and diorite porphyrite. The orebody morphology is simple, occurring in stratoid, sub-tabular and vein-like forms. Ten copper orebodies have been delineated, generally distributed in parallel with a nearly east–west strike. The host rocks of the orebodies are predominantly plagiogranite porphyry, followed by diorite porphyrite, andesite and andesitic porphyrite, with occasional basalt and granophyre. The main beneficial component in the ore is copper, with an average grade of 0.43%. Associated beneficial components include silver and molybdenum, with an average silver grade of 2.37 g/t and molybdenum grade of 0.021%.

2.6.3 Mining method

The open pit mining phase of Phase I has a service life of approximately 9 years. In the 9th year, after the open pit extraction is fully completed, underground mining for Phase II will commence production, with the initial mining level at Lift 200 mL. In the 31st year, underground mining will transition to the Lift 0 mL for extraction. The overall mining sequence follows a top-down approach, and the total service life of the underground mining operation in Phase II is 39 years.

The underground mining design for the Yandong copper mine adopts block caving as the primary mining method. The underground development system consists of a belt incline, auxiliary shaft and access ramp. Ore is loaded by LHDs at the extraction level, transported to ore passes and then dropped to the centralised rail haulage level, where it is loaded into mine cars. The ore is hauled by electric locomotives to the dumping station, crushed and then discharged onto a belt conveyor, where it is transported to the surface through a multi-stage belt conveyor system. Finally, it is delivered to the concentrator via a surface belt conveyor.

For the initial mining level at Lift 200 mL in Phase II underground mining, the following levels will be established: the +216 mamsl undercut and return air level, the +200 mamsl extraction level, the +180 mamsl intake air level and the +160 mamsl rail haulage level. After extraction at this level is completed, mining will transition to the subsequent level at Lift 0 mL, with the following levels: the +16 mamsl undercut and return air level, the 0 mamsl extraction level, the −20 mamsl intake air level and the −40 mamsl centralised haulage level.

2.7 Other mines

The mines currently undergoing applied research and engineering design for block caving mining include the Yechangping molybdenum mine, the Shuangjianzishan silver-lead-zinc mine and the Tongshan mine.

The Yechangping molybdenum mine is located in Henan province. From top to bottom, three concealed lenticular skarn-type molybdenum ore layers and two stratoid porphyry-type molybdenum ore layers have been delineated in the mining area. The general shape of the ore layers is a stacked dome, with a central uplift that slopes outward in all directions and extends until pinching out. The average thickness is 158 m. At present, Yechangping molybdenum mine uses sublevel caving method for extraction, employing an adit-blind inclined ramp development system. The main haulage adit is at the 1,040 mamsl level, with ore transported by electric locomotives pulling mine cars. Due to the poor integrity of rock mass at Yechangping molybdenum mine, the sublevel drifts have been severely damaged, resulting in low production efficiency and high safety risks. The mine plans to transition to block caving mining at depth.

The Shuangjianzishan silver-lead-zinc mine is located in Bairin Left Banner, Inner Mongolia Autonomous Region. It is a typical silver-lead-zinc deposit in the southern section of Greater Khingan Range, with silver resources reaching an ultra-large scale, making it the largest silver-lead-zinc polymetallic deposit in China and even Asia. Within the mining area, a total of 280 orebodies have been delineated. All discovered orebodies are concealed, with the top of the orebodies buried at depths ranging from 25 to 600 m on average. The main orientation of the orebodies strikes northwest, dips southwest, with relatively steep dip angles, exhibiting attitudes and dips of 225°–259° < 44°–61°. The average grades of primary and associated minerals identified within the mining rights area are 138.98 g/t Ag, 1.05% Pb and 1.48% Zn. Shuangjianzishan silver-lead-zinc mine is a newly developed mine, and it is planned to adopt the block caving method for extraction.

The Tongshan mine is located in Heilongjiang province. Four main orebodies, designated No. I, No. II, No. III and No. V, have been delineated. The No. I orebody, mined by open pit methods, was fully extracted by the end of 2023. The No. II orebody, mined using the sublevel caving method without sill pillars, was completed and put into production in March 2025. The No. III and No. V orebodies are newly explored and are currently in the feasibility study stage. The No. III and No. V orebodies are large in scale, with depths ranging from 190 mamsl to −1,658 mamsl. The No. III orebody thickness ranges from 15 to 306 m, averaging 151 m, and the average copper grade is 0.373%. The No. V orebody horizontal thickness ranges from 2 to 448 m, averaging 216 m, and the average copper grade is 0.468%. The orebody occurs at elevations between −127 and −1,525 mamsl. For the No. III and No. V orebodies, the mine intends to adopt the block caving method for extraction.

3 Research progress and development trends of block caving mining technology

Block caving is a high-technology mining method, involving key technologies such as caveability assessment of rock mass, fragmentation prediction, draw control, support of bottom structures, rock mass preconditioning, caving monitoring and prevention and control of mud rush hazards. To promote the application of block caving mining technology in China, extensive research in this field has been carried out.

3.1 Major research progress in China

3.1.1 Caveability assessment and fragmentation prediction for rock mass

The caveability of rock mass is a key factor affecting the successful application of block caving. At present, caveability assessment mainly employs engineering experience analogy, similar simulation experiments and numerical simulation methods, which are primarily qualitative or semi-quantitative. Standards for caveability classification are established based on engineering rock mass quality indices such as RQD, Q value, RMR value and MRMR value. Caveability is generally classified into five levels: extremely difficult to cave, difficult to cave, moderately caveable, easily caveable, and extremely easy to cave (Wang et al. 2014).

Jian et al. (2025) proposed an improved RMR14 evaluation method by modifying the evaluation indices of the RMR14 method and using continuous function values to address the limitation of obtaining some evaluation indicators relying excessively on evaluators' experience. They selected the improved RMR14 value and the RQD value as evaluation factors using a dual fuzzy analytic hierarchy process (F-AHP). These factors were normalised, quantified and clarified to determine their comprehensive weights, thereby establishing a caveability evaluation system for ore-rock mass.

Fragmentation prediction in block caving requires a thorough understanding of the fragmentation mechanisms during ore-rock caving and draw processes, as well as the factors influencing fragmentation. The internationally renowned software for fragmentation prediction is BCF (Block Cave Fragmentation).

Guo et al. (2024) developed an initial fragmentation prediction software system based on the fundamental theories of primary fragmentation prediction in block caving. The system was developed using the C++ language on the DIMINE software platform. It comprehensively considers the spatial geometric parameters of joint systems and the influence of in situ stress, supporting the analysis of initial fragmentation results from perspectives such as block volume, equivalent size and block shape.

3.1.2 Draw control

Draw process management is a crucial aspect of production in block caving mines. By formulating a reasonable draw plan and ensuring its strict implementation by LHDs at the drawpoint level, the caving rate of the overlying ore-rock mass can be effectively controlled, and the grade of the drawn ore can be maintained in balance. Currently, almost all large-scale block caving mines globally use software for daily draw management, with PCBC™ (Dassault Systemes 2023) being the most widely used. This software was developed based on Laubscher’s draw theory.

Some domestic research institutions and scholars have also conducted research on the development of draw control and management software for block caving mines. Li et al. (2017) carried out research and development on a draw control system for block caving. By analysing the workflow of draw management in block caving, they developed a draw management system using the SQL Server database, interactive chart tools, and the C# programming language. This system enabled functions such as calculating optimal draw height, responsible ore volume and average grade; managing drawpoint status and draw tonnage; generating daily and monthly production reports; graphical analysis of draw plans and actual draw data; and graphical analysis of draw height. This provided technical support for achieving fast, efficient and modern draw management.

Zhu et al. (2017), aiming to achieve scientific and reasonable draw control and management in block caving, developed an integrated draw optimisation control and intelligent management system for block caving using the C++ programming language and the hoops visualisation toolkit.

3.1.3 Caving process simulation and monitoring

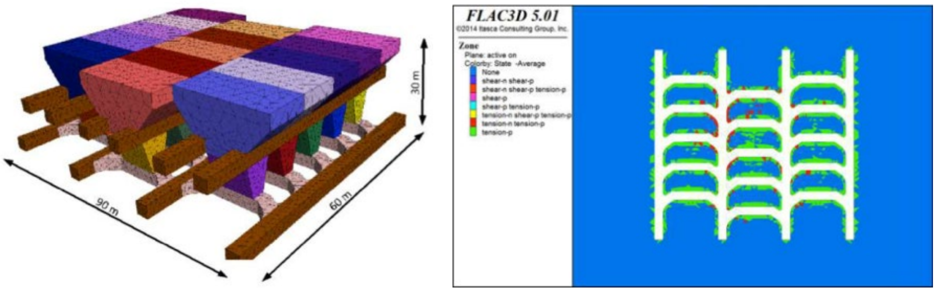
During the block caving mining process, as ore is caved and extracted, the overlying surrounding rock and the surface will also undergo caving, ultimately forming a surface subsidence zone. To accurately understand the development process of rock mass caving in block caving mines, previous scholars have conducted extensive research using numerical simulation methods. Currently, the most representative approaches are FLAC3D coupled with the IMASS module and the MassFlow module, both developed by ITASCA (Cancino et al. 2024). Huang et al. (2025) constructed a large-scale, refined three-dimensional numerical simulation of an ultra-large-scale block caving mine, using FLAC3D to simulate the development of caving body and the spatiotemporal evolution characteristics of surface rock movement throughout the mining lifecycle. The safety of surface structures was evaluated based on composite rock movement standards. Chinese scholar Li Lianchong et al. (2011), using the self-developed RFPA2D software, also conducted research on the fundamental laws of rock mass caving in deep, large-scale block caving mining.

Currently, the monitoring of caving roof in block caving mines mainly employs methods such as open hole method, time-domain reflectometry (TDR), microseismic monitoring and intelligent beacon technology. In China, the Pulang copper mine established a comprehensive integrated monitoring system during its early production stage, including a 3D laser scanning system for surface subsidence monitoring, a TDR system, and a microseismic monitoring system (Wang et al. 2018). This system effectively enabled the monitoring of caving process before cave breakthrough to the surface. During the extraction at Lift 410 mL of the Phase II project at the Tongkuangyu mine, a microseismic monitoring system with dynamic sensor adjustment was implemented (Wang et al. 2025). As the undercut advanced, microseismic sensors were progressively added to achieve three-dimensional caving monitoring. This system has played an effective guiding role in ensuring safe production at Lift 410 mL of Tongkuangyu mine.

3.1.4 Bottom structure support control

The bottom structure provides safe access for ore extraction operations (extraction drifts and drawpoint drifts) in block caving mines and is typically characterised by a long service life, high support strength and high maintenance costs. The service life of bottom structures must ensure the complete extraction of the overlying caved orebody. Its safety and stability are primarily affected by multiple factors, including the inherent strength and integrity of rock mass, undercut blasting, secondary breaking blasting, the self-weight of the overlying caved rock masses, horizontal tectonic stresses and the disturbance stresses induced by caving extraction. Affected by the disturbance from caving extraction, the bottom structures may experience cracking, spalling, and in severe cases, even collapse failure, which directly impact the safe production and economic benefits of block caving mines. To ensure long-term stability of bottom structures, enhanced support measures are typically required during its construction, including rock bolts, cable bolts, shotcrete with wire mesh, steel arches and reinforced concrete linings.

Li et al. (2020) conducted research on the instability factors and support countermeasures for bottom structures in block caving. Addressing the instability issues in the deep mining area of the mine, they used a finite element software to study the stress distribution of bottom structures during the undercutting process and proposed a combined support scheme for the bottom structures. Xia et al. (2020) investigated the catastrophe mechanism of bottom structures under high horizontal in situ stress in block caving. They found that under high horizontal in situ stress, the bottom structures exhibit a stress pattern of 'first compression, then tension'. As the undercut area increases, the concentration of compressive and tensile stresses becomes increasingly evident, manifesting in actual production as repeated weighting phenomena of the bottom structures. Liu et al. (2021) conducted research on the stability monitoring of bottom structures in block caving. Using microseismic monitoring and stress monitoring technologies, they monitored the bottom structures at the Pulang copper mine, analysed the stability variation patterns of bottom structures during the extraction process, studied the effects of undercut advancement and tectonic stress on the stability of bottom structures, and assessed the risk level of bottom structure instability. Figure 4 shows the bottom structure model of block caving and the simulation result of plastic zone after undercutting.



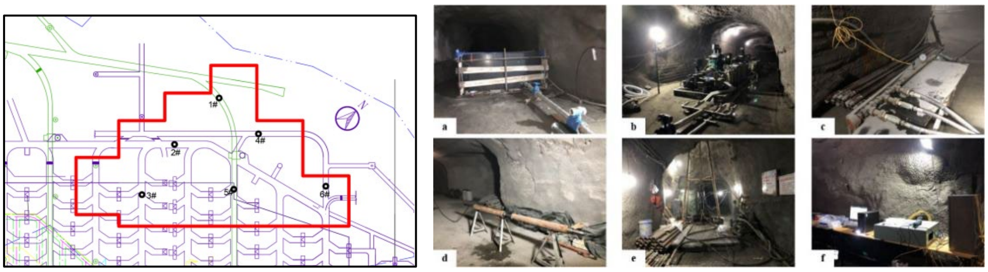
(a) (b)

Figure 4 Numerical simulation on stability of bottom structure in block caving mine (Fan et al. 2020). (a) Bottom structure model; (b) Distribution of plastic zone in bottom structure

3.1.5 Rock mass preconditioning

As block caving mines advance to greater depths, they may face risks such as an increase in boulders, slowing or even cessation of caving. Meanwhile, some low-grade hard rock metal deposits are also being explored for block caving mining, which places higher demands on preconditioning technologies. Block caving mines, such as El Teniente and Chuquicamata in Chile, and Cadia East and Northparkes in Australia, have carried out experimental research and applications of preconditioning technologies, primarily using hydraulic fracturing and confined blasting. These methods have played a positive role in promoting rock mass caving, reducing boulder percentage, and mitigating seismicity in the bottom structures (Catalan et al. 2012). In China, only the Tongkuangyu mine has conducted experimental research on hydraulic fracturing preconditioning technology (Liu et al. 2022).

During the transition period from Lift 530 mL to Lift 410 mL in the Phase II project at the Tongkuangyu mine, hydraulic fracturing preconditioning tests were carried out in the initial mining areas of No. 5 and No. 4 orebodies at Lift 410 mL to ensure stable production rate during the transition. This work was completed collaboratively by China ENFI Engineering Corporation and Tongkuangyu mine of North Copper Co., Ltd (Li et al. 2024). Figure 5 shows the layout plan of hydraulic fracturing preconditioning project in the initial mining area of No. 4 orebody at 410 mL level of the Tongkuangyu mine. Six hydraulic fracturing boreholes were arranged (Figure 5a). Two high-pressure plunger pumps with a maximum flow rate of 159 L/min and an allowable pressure of 55 MPa were used on-site for water injection. A monitoring system was deployed to monitor parameters such as pressure and flow rate during the injection process, while a microseismic monitoring system was simultaneously used to capture microseismic signals during the hydraulic fracturing tests. During the field tests, fracturing was carried out section by section with an interval of 1–1.5 m. A comparison of borehole wall images before and after hydraulic fracturing revealed significant new fractures. The minimum fracture initiation pressure was 3.2 MPa, the maximum was 42.4 MPa, and the average was approximately 23.75 MPa. The minimum stable water injection pressure was 2.1 MPa, the maximum was 40 MPa, and the average was approximately 20.02 MPa. The injection flow rate was mainly controlled by the number of high-pressure injection pumps in operation and valve adjustments during the tests, with flow rates ranging from 250 to 300 L/min for most of the tests. Statistical analysis of caving rate and boulder percentage at drawpoints showed that the caving rate was significantly increased, effectively ensuring continuous ore extraction from the initial mining area at Lift 410 mL of Tongkuangyu mine. Additionally, the boulder percentage was reduced by approximately 50%, and the issue of boulders jamming drawpoints at medium and high levels was significantly alleviated.



(a) (b)

Figure 5 Hydraulic fracturing project in the initial mining area of No. 4 Orebody at 410 m Level. (a) Layout of hydraulic fracturing boreholes; (b) Equipment system

3.1.6 Prevention and control of mud rush hazards

Mud rush at drawpoints is among typical hazard risks in the production process of block caving mines, particularly severe in mines with well-developed Quaternary unconsolidated materials on the surface and high rainfall. Globally, several mud rush hazards have recently occurred in block caving mines, such as at the GBC block in the Grasberg mining area in Indonesia, resulting in casualties among underground personnel and disruption of production. In China, the Pulang copper mine has experienced multiple underground mud rush incidents of varying scales since 2019 (Niu et al. 2020), which not only pose significant hazards to mine safety production but also increase the dilution rate of extracted ore, affecting the mine's economic benefits.

Researchers from Kunming University of Science and Technology have conducted systematic research on the occurrence mechanisms and prevention measures of mud rush hazards at the Pulang copper mine (Niu et al. 2020). The Pulang copper mine has an average annual rainfall of 619.9 mm, with rainfall during the rainy season (May to October) accounting for 87.1% of the annual total. The maximum rainfall occurs at elevations between 3,400 and 3,600 mRL, with precipitation reaching 1,000–1,200 mm. The surface of the Pulang copper deposit is covered by a Quaternary unconsolidated layer with a thickness ranging from 0–75 m, composed primarily of glacial till, residual and slope deposits and a small amount of alluvial and proluvial material. Figure 6 shows the surface subsidence zone at mine area during the 9th underground mud rush incident at Pulang copper mine. Investigation and analysis of the locations where mud rush hazards occurred at the Pulang copper mine indicate that the affected areas are mainly concentrated near five major faults in the initial mining area, and mud rush events tend to occur at drawpoints with a low boulder percentage. Currently, the Pulang copper mine has implemented measures such as comprehensive surface movement area treatment, draw optimisation, and a mud rush hazard monitoring and early warning system (Zhu et al. 2023), which have effectively prevented and controlled the risk of underground mud rush hazards.

Figure 6 Surface subsidence zone at mining area during the 9th underground mud rush incident at Pulang copper mine (Huang 2022)

3.2 Development trends in block caving mining application in China

As a high-technology, large-scale mining method, block caving can achieve production capacities comparable to those of open pit mining. It is currently one of the most ideal methods for mining low-grade, deep-buried hard rock ores and is expected to remain so in the foreseeable future.

3.2.1 Application scenarios

3.2.1.1 Mining of deep, large, low-grade deposits

As shallow mineral resources are increasingly depleted, accessing resources at greater depths has become an inevitable path for mining development. Copper deposits in China are generally characterised by a scarcity of high-grade ores. In particular, large porphyry copper deposits (accounting for about 35% of total resources) typically have low ore grades, generally around 0.55%. To ensure the secure supply of strategic mineral resources such as copper, block caving mining technology has become the preferred method for mining deep, large, low-grade copper deposits.

3.2.1.2 Mines from open pit to underground mining

As open pit mining operations approach their end, they face the transition from open pit to underground mining. For mines with low grades and poor economic efficiency, adopting backfill mining may involve constructing new backfilling plants and incurring high backfilling costs, which directly impacts the mine's economic viability. In contrast, adopting block caving mining can achieve safe and efficient extraction of deep ore resources while ensuring production rate. During the production from open pit to underground mining, some risks for underground caving operation such as mud rush/water inflow hazards and potential airblast deserve close attention.

3.2.2 Technological trend

The high level of global mining industry interest in block caving mining technology has driven its continuous renewal and development. At the same time, the ongoing advancement of block caving technology has contributed to the increasing number of block caving mines worldwide, with industry development and technological progress complementing each other.

Block caving mines and their associated mining technologies generally exhibit the following development trends:

- Increasingly larger mine production rate. Block caving mining technology is already the underground mining method with the largest production rate. Several ultra-large-scale block caving mines are currently under construction or have been realised, such as the Chuquicamata mine in Chile, which transitioned from open pit to underground block caving mining with a designed production rate of approximately 140,000 tonnes per day (50 million tonnes per year).
- Increasingly larger mining lift heights. The Cadia East mine in Australia has designed caving blocks with maximum lift heights of up to 600–800 m and are in production (Catalan et al. 2012), whereas block caving mines in China generally have lift heights of less than 400 m. Increasing the lift height can reduce the number of lifts from top to bottom and decrease development work, thereby lowering mining costs. However, the selection of lift height must be determined based on a combination of factors, including the deposit occurrence conditions, the mine's technical level and operational capabilities.
- Growing number of hard rock mines using block caving. With the development of assisted caving technologies and preconditioning techniques, an increasing number of hard rock mines have adopted block caving in a technically and economically feasible manner. Preconditioning technologies can enhance the development of internal fractures within the orebody of hard rock mines, improve caving characteristics, promote caving, reduce boulder percentage and mitigate seismicity.

- Increasing levels of automation and intelligence in mines. The application of automated and intelligent equipment (such as LHDs, electric locomotives, drill jumbos, and explosive charging vehicles), as well as caving monitoring and draw control software and hardware, has significantly advanced the level of automation and intelligence in block caving mines.

4 Conclusion

Block caving is a large-scale, low-cost underground mining technology. Since its introduction to China in the 1960s, it has achieved considerable development. Currently, there are three block caving mines in production in China, and six mines under construction or in the planning stage. Block caving mining technology will play an increasingly important role in the development of deep, low-grade, large deposits in China, as well as in scenarios such as the transition from open pit to underground mining. Block caving is characterised by its high technological complexity. Technological trends in block caving are supporting future increases in production rate, the potential for larger lift heights, the applicability of preconditioning techniques to broaden the application of caving methods, and lastly, the operational technologies enabling automation and intelligence in mines. Continuous research is still required in areas such as draw control and management, caving monitoring, ground control of bottom structures, rock mass preconditioning, mud rush hazard prevention and control, and mine automation and intelligence. Block caving mines in China are expected to evolve towards larger scales, higher levels of intelligence and improved safety.

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