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Oyu Tolgoi: engineering a Mongolian caving dynasty

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Abstract

Oyu Tolgoi, located in the South Gobi region of Mongolia, is a world-class mining and processing complex jointly owned by the Government of Mongolia (34%) and Turquoise Hill Resources (66%). Rio Tinto owns 50.8% of Turquoise Hill Resources and is the Manager. Rio Tinto provides extensive and critical management services and support for the operation.

Oyu Tolgoi comprises multiple copper, gold and molybdenum deposits located within a more than 23 km-long structural corridor, the bulk of the known deposits requiring underground extraction. Surface mining commenced at Oyu Tolgoi in 2011 and first copper concentrate was produced in 2013. Mining operations have now started from underground following the commencement of production ramp-up in January 2022 of the 95,000 tonnes per day Hugo North Lift 1 block cave mine. Whilst surface mining will continue into the future, underground mining operations are expected to underpin the business for many decades to come and will make Oyu Tolgoi amongst the largest copper producers in the world.

Production from Hugo North Lift 1 is the culmination of more than 20 years of investment in the project. To date, more than 100 km of underground development has been completed, three shafts have been sunk and a significant crushing and material handling infrastructure has been installed to support the initial stages of underground production. Construction of the remaining infrastructure (additional two ventilation shafts, second primary underground crusher, conveyors systems to surface and concentrator upgrade) is continuing in parallel with production ramp-up.

The underground project has been complex; including sourcing and developing the technical, project management, construction and operational capability from around the world that is required to undertake a project of Oyu Tolgoi's magnitude and complexity, addressing the impacts of the COVID-19 pandemic and changes to the extraction level design in the initial underground mining area during construction. Fundamental to the project's success has been the commitment of the more than 20,000 people who have been involved in the project, but especially the Oyu Tolgoi's investment in Mongolian capability, including the establishment of a world-class Mongolian underground mine workforce and supporting mining and construction service industry and in-country engineering and technical capability. Oyu Tolgoi establishes Mongolia as the next centre of large-scale block cave mining in the world.

1 Introduction

Oyu Tolgoi is a world-class mine in the Gobi Desert of Mongolia. It will become a world-class underground mine in the next 10 years. The underlying resources at Oyu Tolgoi will underpin many decades of mining and will position Mongolia as a centre of underground mining and processing expertise. Oyu Tolgoi's history of discovery, development and operation has been complex. Its success is testament to the dedication and perseverance of its owners, the Government of Mongolia, Turquoise Hills Resources (formerly Ivanhoe Mines) and Rio Tinto. More than 20,000 Mongolian and international employees and contractors have worked at Oyu Tolgoi over the last 20 years; some of the very first employees are still working at Oyu Tolgoi today. This is a story of the making of a Mongolian mining dynasty.

2 Exploration and discovery

Whilst the potential for copper mineralisation in the South Gobi Desert of Mongolia was first recognised by Mongolian and Soviet geologists in the late 1950s, it was not until 2001 that Ivanhoe Mines' geologists first intersected high-grade copper-gold mineralisation at Oyu Tolgoi. The initial discovery of the Oyut deposit was quickly followed by the discovery of deeper, but even higher grade copper-gold mineralisation at the Hugo Dummett deposit to the north in 2002. In 2007, additional copper-gold-molybdenum mineralisation was identified to the south at Heruga. Collectively, these discoveries define a 23 km-long zone of mineralisation located between surface and greater than 2,000 m depth. Mineralisation is open at depth and along strike – there are currently sufficient resources defined to support many decades of mining (Figure 1).

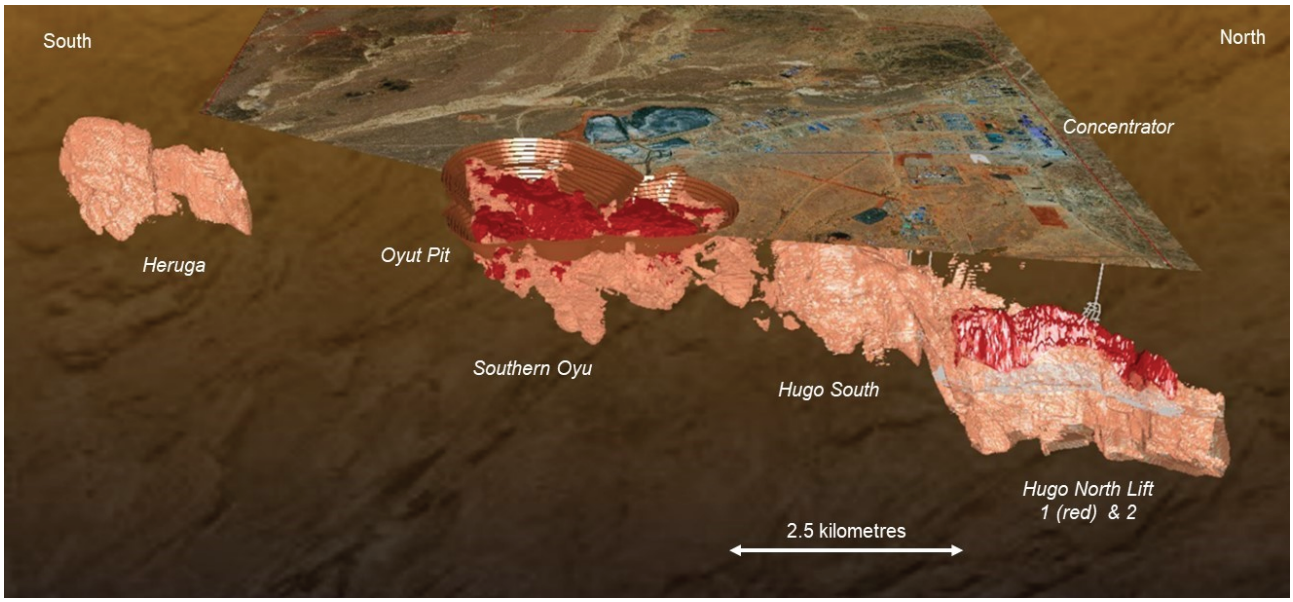


Figure 1 Section view of Oyu Tolgoi deposits (looking west)

3 Project development and start of mining

Recognising that large-scale underground mining is key to the long-term success of Oyu Tolgoi, Ivanhoe Mines began sinking an exploration shaft (Shaft 1) adjacent to the Hugo Dummett deposit in 2005 to accelerate underground evaluation and development of the Oyu Tolgoi deposits. The potential of Oyu Tolgoi was also evident to Rio Tinto – it became a strategic partner in the Oyu Tolgoi project in 2006, initially providing funding for ongoing evaluation, but later provided technical and management support to the project.

As project evaluation progressed, an intense period of negotiations ensued between Ivanhoe Mines, Rio Tinto and the Government of Mongolia to determine how the three project participants would work together to bring Oyu Tolgoi into production. These negotiations culminated in the Oyu Tolgoi Investment Agreement in October 2009 that paved the way for the start of mining at Oyu Tolgoi. The agreement established that the Government of Mongolia would own 34% of the project with the remainder held by Turquoise Hill Resources (TRQ, formerly Ivanhoe Mines Ltd), with Rio Tinto a shareholder of TRQ. Rio Tinto's expertise and resources would underline the management expertise and support required to complete the project. Rio Tinto subsequently became the majority shareholder in TRQ (50.8%).

The first phase of mining comprised an open cut mine at the Oyut pit (Oyut). Ore is crushed through a primary crusher and conveyed to a 38 million tonnes per annum concentrator for processing. Copper concentrate is bagged and then trucked 105 km south to the Chinese border for pick-up by largely Chinese smelter customers. Waste from the concentrator is stored in tailings storage facilities adjacent to Oyut constructed primarily from pit waste rock. Mine operations are supported by an onsite heating plant, accommodation, and catering for 10,000 employees, office and communications systems, an airport and a sealed roadway to

the Mongolia-China border. Water for mining operations is sourced from the Gunii Hooloi aquifer 35 km from Oyu Tolgoi and electricity is sourced from Inner Mongolia, China.

Planning for a large block cave mine at the Hugo deposit continued unabated during this period. Sinking commenced on a second shaft (Shaft 2) and, following completion of Shaft 1 to a final depth of 1,385 m in 2007, lateral development was undertaken to establish a platform for underground evaluation and exploitation of the Hugo Dummett North deposit. Sinking of a third shaft (Shaft 5) began in order to provide additional ventilation capacity for the underground mine.

Surface mining of the Oyut pit commenced in 2011 and first copper concentrate was produced in 2013. Surface operations quickly ramped up to 41 million tonnes per annum, establishing Oyu Tolgoi as a world-class mining operation with strong safety, environmental and community credentials. As examples, Oyu Tolgoi operations achieved an 'all injury frequency rate' of 0.14 in 2021, 88.3% water recycling in its operations, reducing water consumption to 0.38 kl per tonne of ore processed and reached Mongolian employment rates of greater than 97% of its 16,000 person workforce, including 16% female employees.

4 The Hugo North Lift 1 underground project approval

Notwithstanding the success of surface operations, work on the underground project was suspended in 2013 due to impasses reached between shareholders in relation to a number of matters about the development of the project. Approximately 10 km of lateral development had been completed and Shafts 2 and 5 were partially sunk at the time of suspension. The project was placed in care and maintenance. After a period of further negotiations, the Government of Mongolia and other shareholders reached agreement in 2015 that paved the way to recommence construction on the underground project. Notice to proceed with the recommencement of the underground project was approved in July 2016.

The underground project approved by the Government of Mongolia and shareholders represents the first phase of underground mining at Oyu Tolgoi and is based on extracting the first and uppermost 500 m-high lift of the Hugo North (Hugo North Lift 1) deposit using the block caving mining method. The project envisaged a 2,500 m long × 300 m wide block cave mine at 1,300 m depth that would ramp-up to 95,000 tonnes per day production rate, making Hugo North Lift 1 one of the largest underground mines in the world. When complete, the project would comprise five shafts, each between 1,100 and 1,300 m deep, nearly 200 km of lateral development, and a material handling system comprising an underground trucking system feeding two 50,000 tonnes per day capacity gyratory crushers, with ore haulage to surface via Shaft 2 (30,000 tonnes per day) and a greater than 95,000 tonnes per day capacity inclined conveyor system. The underground project also includes an upgrade to the Oyu Tolgoi concentrator to handle the higher grade underground ore.

5 2016 mine design

5.1 Unique design considerations

The 2016 HNL1 block cave layout comprised an initial mining area (Panel 0) located near the centre of Lift 1 coincident with the high-grade core of the deposit and two large but lower-grade panels to the north (Panel 1) and south (Panel 2) (Figure 2). Undercutting was to be initiated in the middle of Panel 0 and advance on two fronts to the north and south to the Panel 0 boundaries. Undercutting would then continue across the Panel 0 boundaries, initiating mining in Panels 1 and 2, allowing mine production to ramp-up to 95,000 tonnes per day over nearly eight years.

The mine design is based on the following five mine levels, from top to bottom: apex level to allow verification of undercut blasts to minimise the chance of residual pillars in the undercut, undercut level, extraction level, ventilation level and haulage level with central (in-footprint) orepasses on the extraction level to the haulage level. The 2016 mine adopted the El Teniente drawpoint layout on 28 × 15 m spacing.

The geological and geotechnical models that the original 2016 mine design was based upon were informed by the information then available, which included surface drilling, underground drilling and underground

development, including one development drive that crosscut the orebody in the vicinity of the initial mining area. This information indicated that the HNL1 extraction level would be characterised by variable but overall moderate rock mass strengths. Combined with the high ambient and cave-induced stresses, HNL1 was assessed as being characterised by low rock mass strength to stress ratios. As a result, the 2016 mine design sought to manage the induced stresses during mining and protect the rock mass from those stresses. Based on a risk assessment process and utilising lessons learned from other caving operations around the world, the following key elements were included in the 2016 mine design:

- Advanced undercut with minimal lead-lags and undercut advancing perpendicular to principal stress.
- Extraction drives parallel to principal stress.
- Mining of Panel 0 to confirm mining assumptions before progressing to additional panels.
- Advancing the cave on two fronts (north and south) to provide greater operational flexibility.
- An apex level (drives along the top of the major pillar) to allow verification of undercut blasts to minimise the chance of residual pillars in the Big W layout.
- Minimising the size of extraction level drives to maximise residual pillar size and optimising drawbell spacing for reserve recovery and extraction level stability.
- Intensive ground support installed across the mine footprint, including extensive cable bolting, heavy duty mesh, resin-encapsulated ground support and reinforced shotcrete, with heaviest support to be installed in areas of poorer ground.
- Extensive monitoring systems positioned across the mine footprint to allow early detection of rock mass deformation, including extensometers, flow markers and microseismic arrays.

Another key design consideration was ensuring adequate productivity and flexibility for undercutting, drawbelling and cave draw; recognising that compliance with caving rules and achieving planned undercutting rates and cave draw compliance are fundamental to a smooth cave ramp-up. This led to the inclusion of central orepasses and a haulage level beneath the extraction level to allow efficient material handling from the extraction level. The orepasses, which were to be installed ahead of undercutting, were located beneath the area of undercut initiation to minimise the risk of caving-induced damage.

Finally, a comprehensive program of orebody knowledge data collection and monitoring was incorporated into the project execution phase to refine and calibrate the geological and geotechnical information.

6 Construction of the HNL1 underground mine

The underground project execution essentially required concurrent underground development and construction. Earliest development focused on shaft sinking, mine access and undertaking the mass excavations for underground infrastructure. Construction focused on the mine infrastructure that would progressively enable a ramp-up in underground development rates. Early development was dependent on Shaft 1, which was both the intake and exhaust for the underground workings and the sole access for people and materials and hoisting of development waste. Development rates were constrained to about 800 m equivalent of lateral development per month. Installation of a range of underground facilities, including workshops and offices, dewatering and underground magazines helped improve the efficiency of underground work. The completion of Shaft 5 provided additional ventilation capacity and a small increase in development capacity to approximately 1,200 m equivalent per month. Completion of Shaft 2 sinking, equipping of the shaft and commissioning of the Shaft 2 crushing system facilitated a step-change in underground development rates to in excess of 1,800 m equivalent per month. This steady ramp-up of development capacity was also enabled by the parallel build-up and upskilling of the project's Mongolian workforce.

The focus of lateral development progressively switched to development of the block cave mine footprint; the apex, undercut, extraction and haulage levels whilst construction focus switched to construction of material handling system 1 (MHS1) – comprising Primary Crusher 1 and material handling system connection to Shaft 2 hoisting. The completion of essential footprint development and the successful commissioning of MHS1 satisfied the bulk of the technical criteria for commencement of underground mining.

Work is currently focused on lateral development for the next mining panels and construction of the remaining underground infrastructure, including Material Handling System 2 and the convey to surface system, sinking Shaft 3 and 4 and the concentrator upgrade.

7 Changes to the 2016 feasibility study mine design

Construction of HNL1 mine has been complex, not surprisingly given the project's technical complexity, its remote location and size. In addition, the project has had to manage the impacts of the global COVID-19 pandemic over the last three years. Of specific interest to the caving community though are the changes to the mine design that were undertaken during mine construction.

As the Panel 0 footprint was developed, additional geological and geotechnical data was collected, including face scans of more than 90% of all development headings. These scans provided detailed geological and geotechnical information, including estimates of rock strength, at a much tighter spacing than the surface drilling. The additional information highlighted that the Lower Fault Splay was more extensive and pervasive than previously understood (Figure 2). It is defined by multiple northwest–southeast trending and moderately northeast dipping zones of low strength rock located across the centre of Panel 0. Importantly, the fault zone intersects the proposed central orepasses in Panel 0, as well as the Panel 0 rim drives and the mid-access drives. The primary concern was the impact of the Lower Fault Splay on the stability of critical infrastructure; specifically, that the loss of the orepasses, rim drives and the mid-access drives during undercutting and cave ramp-up would adversely impact the integrity of the Panel 0 mining area.

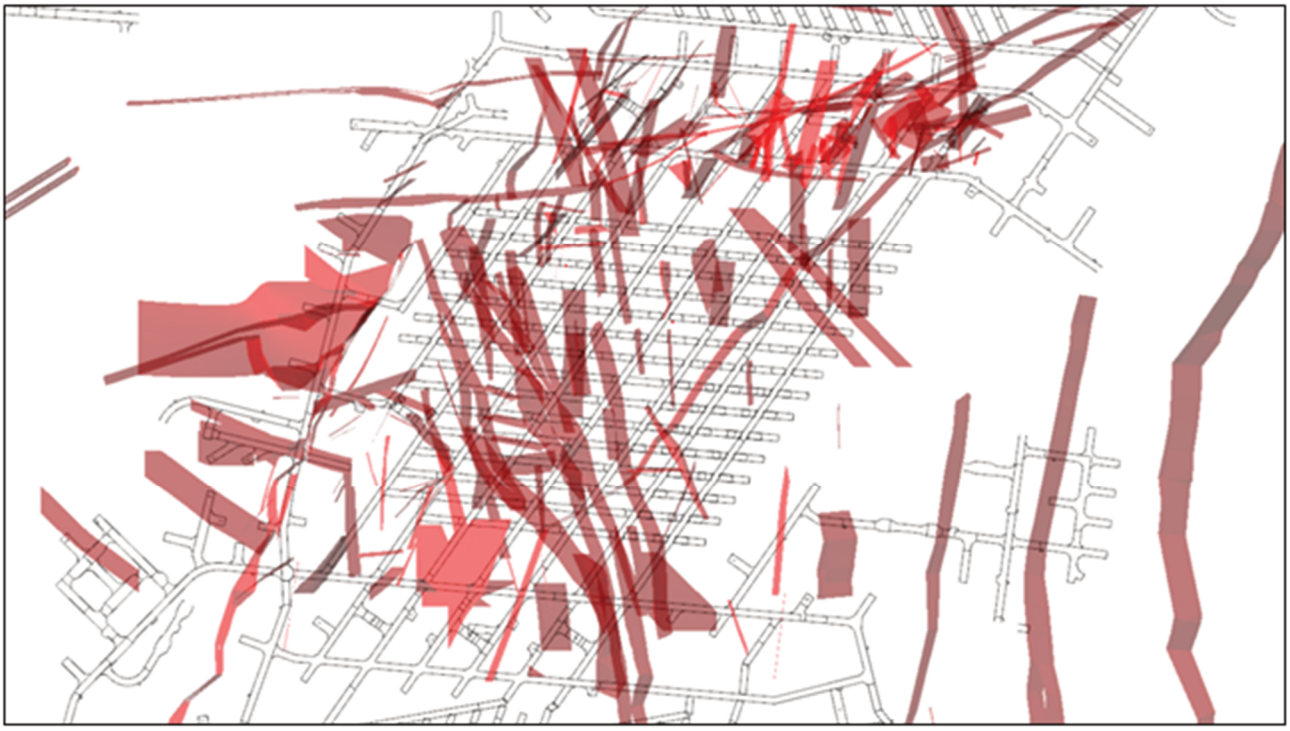


Figure 2 Plan view of the 2020 mine design Panel 0 extraction level, HNL1 showing major structures in red (north to top of page)

A review of potential changes to the mine design to mitigate these risks was initiated. Concurrently, a campaign of rock testing was undertaken to improve the confidence in rock strengths of the different geotechnical domains identified through the updated geological and geotechnical interpretations. Three-dimensional numerical stability modelling of the footprint and associated infrastructure was undertaken, based on the updated structural and geotechnical inputs, which confirmed that a re-assessment of the mine design for the initial mining area was warranted, based on the following risks associated with the 2016 mine design, specifically:

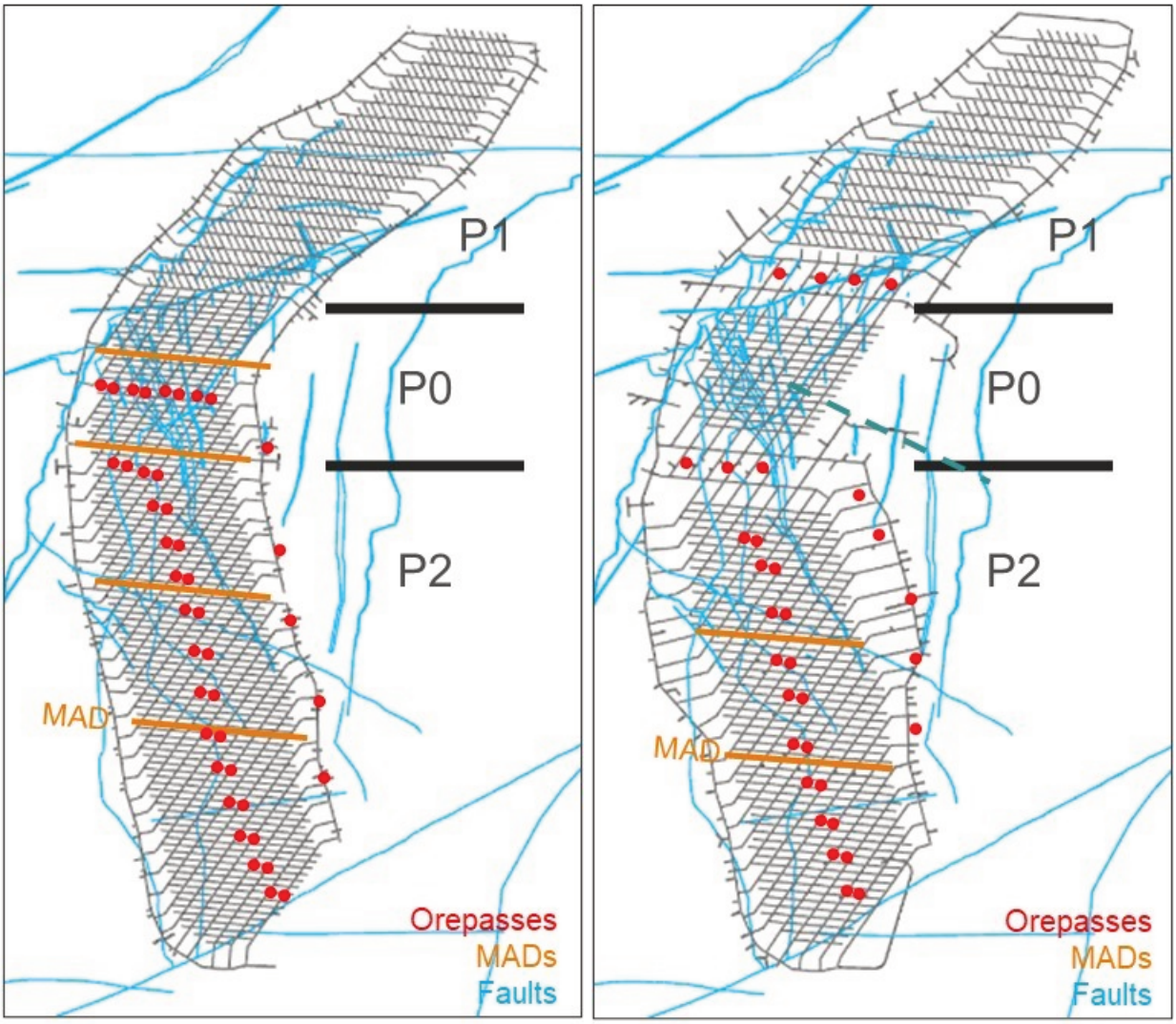
- The orepasses in the centre of the Panel 0 footprint could be seriously damaged during undercutting.
- The undercut and extraction levels would potentially suffer significant damage around the mid-access drives.
- There could be significant damage to the rim drives as the undercut crossed from Panel 0 to adjacent panels.
- Extraction drives and drawpoints in the vicinity of the Lower Fault Splay would likely incur high levels of failure.

As a result, it was concluded that an analysis of alternate designs for Panel 0 was required to identify options to better manage these risks, with the added requirement that any option not delay ongoing construction and production ramp-up. This analysis also considered the risks and business case of the alternate designs, including resource recovery and production profiles relative to the 2016 mine design.

Technical teams from across Oyu Tolgoi, Rio Tinto and TRQ worked together with a wide range of international mining consultants to identify and then evaluate a range of different design options. Further updates were made to the geotechnical models to capture the latest geological and geotechnical data available and three-dimensional numerical modelling was undertaken to assess and compare the design options. The resultant analysis, which included risk-ranged production schedules for each of the design options, provided comparisons of the options across a range of safety, productivity and financial metrics. Finally, a revised mine design (the 2020 mine design) was recommended for Panel 0 that better managed the mining risks, without compromising the timing of Panel 0 production and the production ramp-up of HNL1.

The key changes to the mine design (Figure 3) are:

- Establishing temporary mineable pillars at the northern and southern edges of Panel 0 (within the orebody) and locating the orepasses within the pillars. The underlying haulage level was also redesigned for the new orepass locations. The pillars effectively segment HNL1 into at least three discrete and semi-independent mining blocks and negate the need to undercut across panel boundaries. The pillars were sized to provide sufficient protection for the orepasses for the duration of Panel 0 mining and so that they could be recovered after the orepasses were no longer required, noting further assessment of the pillar recovery options would be undertaken as part of the design review of the remainder of Lift 1.
- Removal of the mid-access drives on the undercut and extraction levels. As a result, additional footprint development had to be undertaken before undercutting could commence.
- Widening of the drawpoint spacing to 31 × 18 m to improve extraction level stability.
- Initiating undercutting in the southwest corner of Panel 0 and maintaining a single northwest–southeast oriented undercut face, thereby maintaining an undercut perpendicular to principal stress and favourable orientation to structure.



(a) (b)

Figure 3 (a) HNL1 2016 mine design, superimposed on 2021 structural model; (b) HNL1 2020 mine design, superimposed on 2021 structural model

All other elements of the 2016 Feasibility Study FS16 mine design were retained and no changes were made to the material handling systems.

After considerable internal and external review, including by Oyu Tolgoi's Geotechnical Review Board (independent subject matter experts), the 2020 mine design was progressed as the most technically feasible. The Panel 0 design has now been fully implemented. Following successful negotiations with the Government of Mongolia and satisfying technical undercut readiness criteria, the start of undercutting commenced in February 2022.

8 Looking Forward: Panel 0 undercutting and production ramp-up

The HNL1 project has now arguably entered its most technically challenging phase – undercutting and production ramp-up. The first drawbell was fired in June 2022 (Figure 4). The next key milestones are achieving critical hydraulic radius (21 drawbells) on the extraction level in 2023 and production ramp-up to 30,000 tonnes per day from Panel 0 in 2025. The critical inputs to production ramp-up include:

- Major hazard management – a major revision of Rio Tinto's Underground Major Hazard control framework, including a range of new group procedures, was completed in 2021 and is being

implemented at Oyu Tolgoi. The underground mine already has relatively advanced personnel monitoring systems, including full personnel monitoring that is integrated with the network of underground refuge chambers and individual carbon monoxide monitors.

- Integrated long-term to short-term planning and scheduling – systems and tools have been developed to synchronise and optimise the mining sequence of undercutting, drawbelling, draw point and roadway construction and production draw.
- Capability building – comprehensive training and onboarding programs have been put in place to establish the core operational competencies required to achieve a smooth and uninterrupted cave ramp-up, including drill and blast, geotechnical and cave management, and asset management.
- Mine monitoring and cave management – data management systems that allow mine management and remote technical experts to access and interrogate the enormous amount of data generated from the mine, including historical geological and geotechnical data, installed ground support, real time and static data from extensometers and microseismic systems as well as undercutting and production performance. These systems have been configured to track compliance to cave rules and identify potential risks associated with the cave.

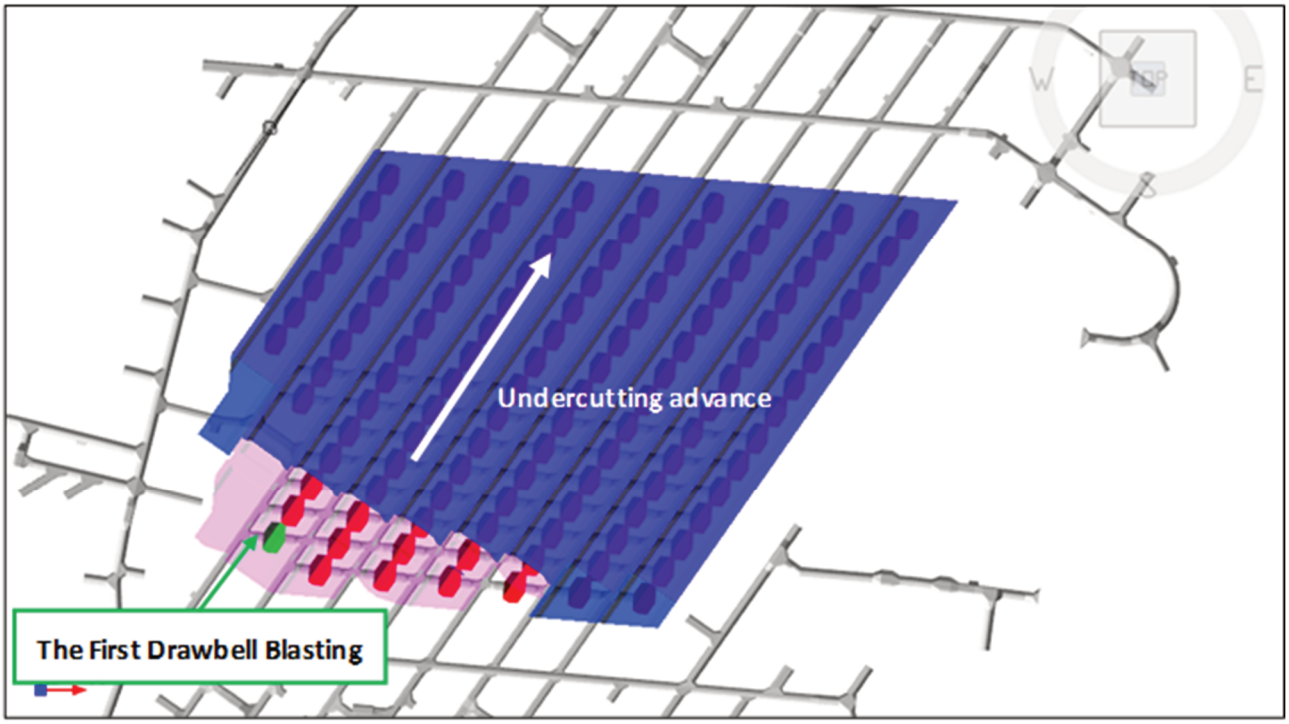


Figure 4 Plan view of the Panel 0 extraction level, HNL1 showing undercut initiation and advance direction (north to top of page)

Oyu Tolgoi's underground operations are underpinned by an extensive wireless network that allows remote access to data from a wide range of monitoring systems, fixed and mobile equipment and infrastructure, and to personnel location. Work is underway to improve integration of the full range of data to enable improved major hazard and emergency response management, predictive maintenance including underground fire prevention and further optimisation of the underground production system.

Likewise, a range of technology improvements are being progressed for the underground mine, including transition to battery electric vehicles (BEV) to eliminate diesel particulates and reduce ventilation demand, Level 9 collision avoidance systems for all underground fleet, ventilation on demand, autonomous loading and hauling and high-speed ground support installation.

9 The next phases of underground mining

Adopting a block cave design for Panel 0 has allowed Hugo North Lift 1 to be broken down into more manageable mining blocks and provides more flexibility in the macro-sequencing of the blocks to achieve ramp-up to 95,000 tonnes per day. The new design also allows lessons from the first stage of mining at Panel 0 to be applied to future blocks.

Based on the lessons already learned from Panel 0, significant additional underground drilling and rock strength testing has been undertaken across Panels 1 and 2 to better understand the extraction level horizon rock mass, including the northern and southern extensions of the Lower Fault Splay. Design work is now focused on developing detailed mine designs for Panels 1 and 2 and for the temporary mineable pillars, including the many trade-offs required to achieve the appropriate balance of mining risk. The rim drives for Panel 2 are currently being developed and the final design for Panel 2 is currently expected to be finalised in late 2022 to early 2023.

Work has also commenced on designing the evaluation program for the second mining lift at the Hugo North deposit (Hugo North Lift 2).

10 Building Mongolia's mining industry

Mongolia celebrates the 100th anniversary of its mining industry in 2022 and it is therefore fitting that Mongolia's Oyu Tolgoi underground mine has commenced its production ramp-up to become one of the world's largest underground mines on this anniversary. However, Oyu Tolgoi is already rapidly transforming the Mongolian mining industry and establishing Mongolia as the next centre of large-scale block cave mining in the world. Oyu Tolgoi is establishing a world-class Mongolian underground mining workforce, supporting a strong national mining and construction service industry, and building in-country engineering and technical capability.

The company has invested heavily in developing its Mongolian workforce; more than 97% of Oyu Tolgoi's 16,000 workforce are Mongolian nationals, exceeding the company's longstanding commitment to the Government of Mongolia of achieving 90% Mongolian employment during operations. This has been possible through Oyu Tolgoi's comprehensive in-house training and development programs and via a concerted program of mentoring and skills transfer from expatriate employees supported by the Rio Tinto Group. In addition, over a hundred Mongolian employees have had the opportunity to work at Rio Tinto's operations around the world, gaining critical mining industry skills. Specifically, Mongolian employees are embedded in the Brisbane-based underground mine design and technical teams and in Rio Tinto's Underground Mining Centre of Excellence to build underground mining capability.

Oyu Tolgoi also provides university scholarships for Mongolians to study in Mongolia and abroad. Since 2011, the company has provided 375 domestic scholarships for Mongolians to study at national universities and 36 international scholarships for Mongolian students to study at international world-class universities. The company also provides a range of programs to build out the pipeline of future employees, including Youth Development, Internships, Graduate Development and Safe School programs.

Both Oyu Tolgoi and Rio Tinto Mongolia are working with the Mongolian University of Science and Technology to establish undergraduate mining and geotechnical engineering degree and postgraduate research programs, in collaboration with Australian and other international universities. Funding for a Rock Mechanics Laboratory at the university and support to attend international mining conferences has also been provided. These programs establish a strong pipeline of mining talent for both Oyu Tolgoi and the broader Mongolian mining industry.

Oyu Tolgoi and Rio Tinto are also actively fostering a greater understanding of block cave mining in the wider Mongolian mining community through sponsored conferences and technical seminars, which help explain the complexities of the Oyu Tolgoi project.

From 2010 to 2021, Oyu Tolgoi's in-country expenditure was US$ 13.4 billion, the largest source of foreign investment in Mongolia. Significantly, 76% of that expenditure has been with local suppliers. Total in-country procurement for the same period was US$ 4.3 billion. The underground project has contributed significantly to this expenditure. The 2016 Feasibility Study indicated the underground project would spend approximately US$ 1.6 billion with local suppliers; however, the project's in-country spend has already exceeded US$ 3.4 billion. This has in part been realised by Mongolian companies partnering with foreign companies to provide a wide range of services and supplies, including underground mine development and construction, further expanding the capability of the Mongolian industry. Oyu Tolgoi has also established a 'Made in Mongolia' program that has delivered a range of items including hygiene, safety and electrical consumables that it would have previously imported.

11 Conclusion

Mining operations at Oyu Tolgoi are now transitioning from surface to underground following the commencement of production ramp-up in January 2022 of the 95,000 tonnes per day Hugo North Lift 1 block cave mine. Underground mining operations are expected to underpin the business for many decades to come and will make Oyu Tolgoi amongst the largest copper producers in the world.

Enormous progress has been made in establishing Mongolia's first block cave mine at Oyu Tolgoi. The underground project has faced many complexities since it restarted in 2016 and progress to date is testament to the commitment of the more than 20,000 people who have been involved in the project so far. Oyu Tolgoi's investment in Mongolian mining capability, including the establishment of a world-class Mongolian underground mine workforce and supporting mining and construction service industry and in-country engineering and technical capability are critical to the future success of the business. Oyu Tolgoi establishes Mongolia as the next centre of large-scale block cave mining in the world, establishing a Mongolian Caving dynasty.