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Global benchmarking of block caves: a super cave update

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Abstract

Over the past two decades, block caving has been applied at greater depths and to significantly taller draw columns and with a substantial increase in scale and productivity. Historic benchmarking does not capture the operational characteristics of the deeper, taller caves that reached peak production after 2003, nor the first cohort of super caves (caves with lift heights >300 m and production rates >70 ktpd) that were at the project stage 20 years ago. There are currently 7 super caves (i.e. design capacity >70 ktpd) either at peak production, in ramp-up or forecast to reach peak production in the early to mid-2030s.

Rio Tinto recently undertook a benchmarking analysis of global block caves using only public sources to supplement in-house caving experience and capture developments in these deeper, taller caves over the past 20 years. This paper presents the results of the benchmarking study and summarises the current state of block caving, with emphasis on the super caves and deep block caves commissioned since 2003. Hugo North Lift 1 in Oyu Tolgoi, Mongolia, provides the primary reference point for scale and depth, with the focus on deep, large caves. However, since the number of super caves is limited, the benchmarking also drew explicitly on smaller, deep block caves of comparable footprint scale and production to Hugo North Panel 0, the first cave mined at Oyu Tolgoi.

All information presented in this paper, including for Oyu Tolgoi, is publicly available.

Keywords: *benchmarking, block cave, super cave, caving, Oyu Tolgoi, Hugo North*

1 Introduction

Previous block caving benchmarks are becoming increasingly outdated. The first cohort of super caves has transitioned into operational mines, and a new cohort of super caves is being studied and developed. In this paper, a *super cave* is defined as a caving operation producing ≥25 Mtpa (≈70 ktpd) with >300 m draw height (as defined by Brown 2007).

Rio Tinto embarked on a benchmarking study to compile and compare publicly available caving information with a focus on current super caves – those at peak production, in development or ramping up. The aim was to supplement in-house caving experience, compare current caving practices and document the progression in key caving metrics over the past two decades. The benchmarking targeted both larger (super) caves and smaller, deep block caves. The study results were used to:

- position Oyu Tolgoi Lift 1 relative to historical and contemporary deep, high-lift caves
- apply global experience to the design and sequencing of future Oyu Tolgoi caves.

1.1 Oyu Tolgoi

Oyu Tolgoi consists of a series of deep and near surface, Cu-Au-Ag-Mo orebodies in southern Mongolia. The Hugo Dummett North (Hugo North) orebody extends approximately 670–1,570 m below surface and is the first orebody to be mined underground at Oyu Tolgoi.

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The Hugo North Lift 1 (HNL1) extraction level lies ~1,300 m below surface and is ramping up to a production target of ~95 ktpd from several panels (Stegman et al. 2022). The Lift 1 design includes four caves, 57 extraction drives, 37 truck chutes, over 1,480 drawpoints and 776 drawbells (Figure 1) (Hanani et al. 2026).

Panel 0 (the central panel) is the first of four panels in production on Lift 1 (the layout of the four panels in HNL1 is shown in Figure 1). The first drawbell in Panel 0 (P0) was fired in June 2022 followed by the commencement of production in March 2023 (Rio Tinto 2025). Panel 0 production has consistently exceeded its 30 ktpd nameplate capacity since 2025, at times achieving > 50 ktpd, and averaging over 35 ktpd in May 2025 (Hanani et al. 2026). Development of a second panel, Panel 2 North (P2N), is progressing, with undercut blasting commencing in April 2025 and the first drawbell fired in August 2025 (Hanani et al. 2026). Multipanel production is expected to lift the total HNL1 throughput to well above > 80 ktpd later this decade.

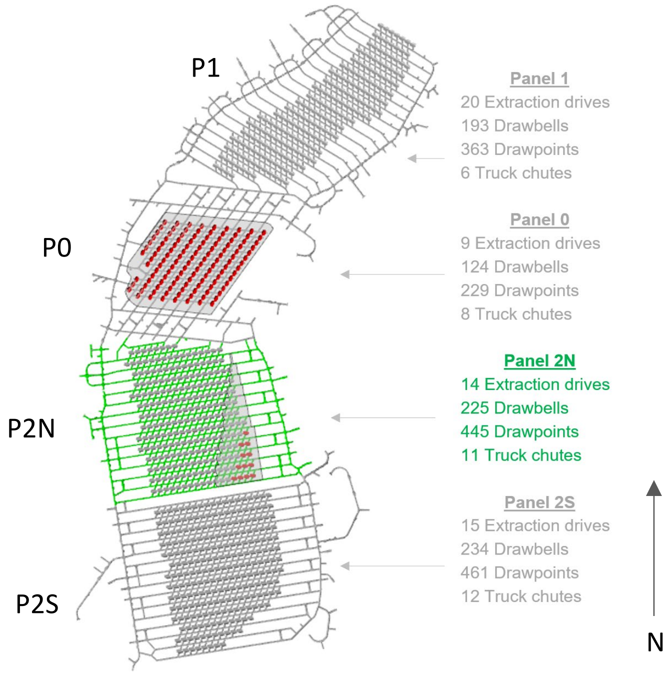


Figure 1 Hugo North Lift 1 cave layout, with blasted drawbells (red), as at the end of February 2026 (Hanani et al. 2026)

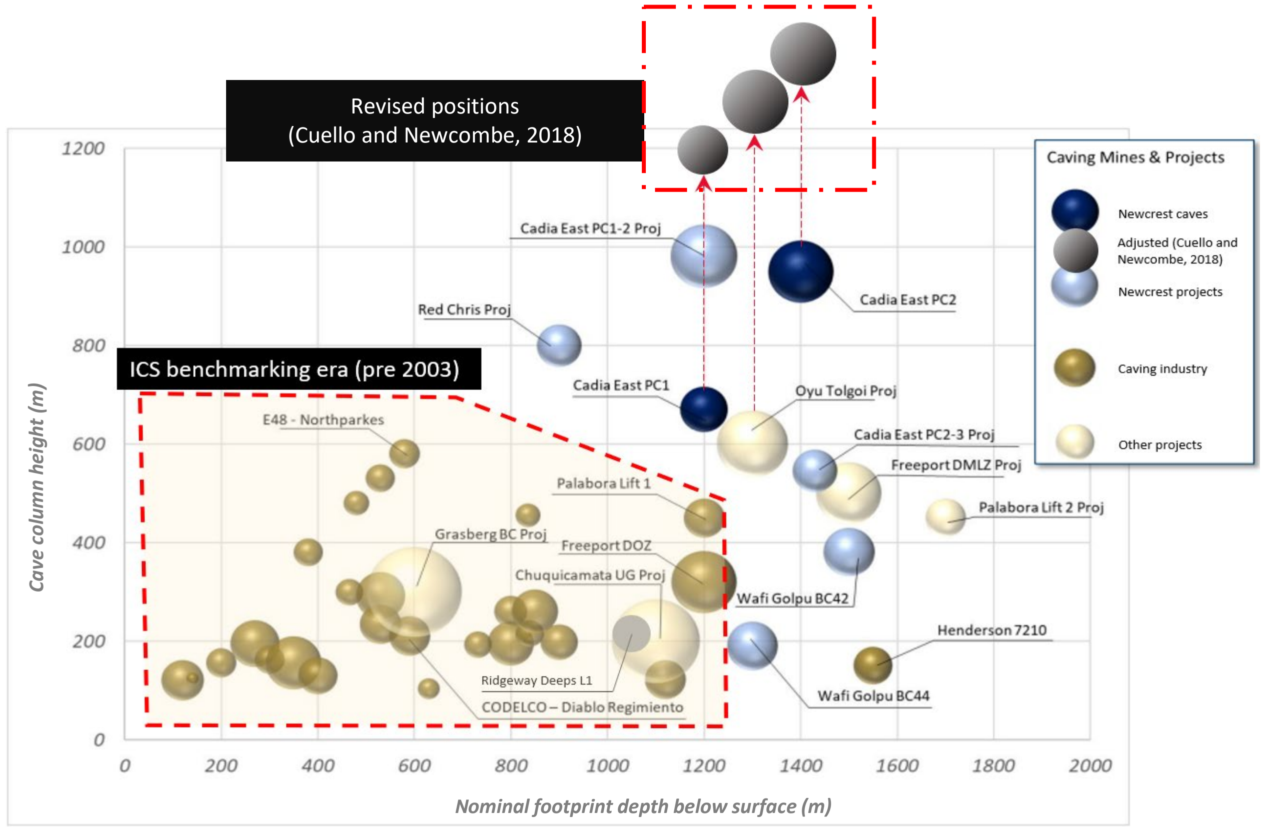
2 Benchmarking

Benchmarking has long been used in block caving to inform design assumptions, assess technical risk and justify capital expenditure for new caves. However, older block caving benchmarks reflect operating caves that were shallower and had shorter lift heights and lower production rates than those being planned and operated today. Since 2003 block caving has undergone a marked step change in depth, cave height, footprint scale and peak production, with a small number of caves now operating within this expanded, super cave range. These changes then also drive increases in scale for other key design considerations including drive size, loader capacity, drawpoint spacing, undercutting and infrastructure stand-off rules.

2.1 Up to 2003

Pre-2003 cave metrics, benchmarked as part of the International Caving Study (ICS), show a progressive increase in cave scale, primarily driven by larger-capacity loaders and higher lifts. Mean drawpoint spacing increased to 15 m and mean extraction drive spacing increased to 27 m, almost double the pre-1990 spacings (Flores & Karzulovic 2000). This increase in drawpoint and drive spacing was driven by the need for footprint stability at greater depths and the larger drive sizes needed for the larger-capacity loaders introduced to improve productivity. The ICS benchmarking also documented concurrent increasing block heights, from a mean of ~100 m prior to 1990 to ~250 m by 2000 (Flores & Karzulovic 2000).

Stage 2 of the ICS (ICS II) compared cave column height and footprint depth for past, operating and planned caves, highlighting the scale of caving experience available at the time (shown in Figure 2). The operating caves that defined this benchmark were materially shallower and shorter than the projects entering study and development in the early 2000s and modern super caves lie well outside the depth and lift height ranges that bounded contemporary caving practice at the time. The ICS II benchmarking graph was revised to capture this by Cuello & Newcombe (2018), adjusting the cave column height to reflect the significant height to surface breakthrough at Oyu Tolgoi and Cadia East (shown in Figure 2).



Bubble size represents production rate.
Data source: International caving benchmarking study stage 2, University of Queensland (2003).

Figure 2 Cave mines and projects depth versus column height (Newcrest 2021, referencing International Caving Study II 2003), with revisions to Oyu Tolgoi and Cadia East column heights after Cuello & Newcombe (2018).

In 2003 the deepest operating caving mines were:

- Deep ore zone (DOZ), 1,000 m deep, 390-500 m block height
- Palabora Lift 1, 1,200 m deep, 450 m block height, which was in its first year of ramp-up and had not yet propagated into the pit (Paetzold et al. 2020)
- Henderson 7,210 Level, which was being developed prior to commencing production in 2005 (Sainsbury & Loring 2013)
- Northparkes E48, with a lift height of 580 m, which was in project development in 2003 and went on to be commissioned in 2010 (Webster et al. 2020).

Prior to 2003 peak production rates for block and panel caves were typically 20–40 ktpd. DOZ only had a peak production rate of 25 ktpd in 2002 (it wasn't until later that the mining reserve and footprint were increased, and the production rate target increased to 50 and then 80 ktpd) (Casten et al. 2020).

2.2 Post-2003

Caving projects developed post-2003 show a coupled step change in cave height, footprint scale and production rates. More recently, significantly deeper, taller and larger caves have been developed, including Cadia East (PC1, PC2, PC2–3), Grasberg (GBC, DMLZ), Chuquicamata Lift 1, El Teniente New Mine Level (NML), Oyu Tolgoi HNL1, Palabora Lift 2 and New Afton C–Zone.

Freeport's DOZ was a trailblazer, showing in 2010 that 80 ktpd production rates were achievable at 1,150 m depth, with tall (350–500 metre-high) draw columns. However, after 2011 the DOZ production rate dropped to 50 ktpd, and it wasn't until 2018 that the >70 ktpd super cave criteria were satisfied at Cadia East PC1 and PC2.

El Teniente's historical output at a district scale has exceeded 80 ktpd combined from several independent, ~200 m lift panel caves. Individually, these mines produced 15–45 ktpd and do not satisfy the super cave production or lift height criteria. In 2003 the district averaged ~100 ktpd from Esmeralda, Reservas Norte (Ten Sub 6), Teniente Sur 4, Diablo Regimiento and Pipa Norte. Esmeralda had the highest peak production of those five mines, averaging 40 ktpd. El Teniente's NML is in the early stages of development, 350 m below current caving operations, and will be El Teniente's first super cave.

Since 2003 production rates have also increased significantly, enabled by larger footprints (allowing simultaneous production from multiple panels) and significantly taller lift heights. Peak production from super caves has now progressed to well above 70 ktpd. Cadia East and Grasberg's DMLZ are currently producing at rates ≥80 ktpd and GBC achieved 150 ktpd in 2023 (Beard et al. 2024). Chuquicamata and El Teniente's NML (including Andesita) have planned production targets ≥130 ktpd.

2.3 Current study

Given the limited number of operating super caves, the study was structured to benchmark both primary super-cave operations and a secondary set of smaller, deep block caves. The primary focus was on super caves of comparable scale to Hugo North Lift 1, defined as copper porphyry caves with actual or planned production rates exceeding 80 ktpd (> 28 Mtpa) and cave heights greater than 300 m. The primary targets mines were Cadia East, Grasberg (GBC and DMLZ), Chuquicamata and El Teniente. To broaden the experience base, the benchmarking also included a secondary group of smaller, historical and non-copper caves, including Palabora, Northparkes, New Afton, Padcal, Pulang, Tongkuangyu, Andina, Ridgeway Deeps, Cullinan, Henderson, Finsch and Argyle.

At the time of the study, Cadia East was the only super cave that had sustained peak production for several years, while DMLZ and GBC reached nameplate production in 2023. As a result, there is limited publicly documented operating experience from super caves at steady-state production over extended periods. This constraint reinforces the continued relevance of earlier deep caving experience from smaller operations. In particular, Henderson demonstrated that block caving could be successfully applied at depths of 1,300– 1,550 m, providing an important foundation for the design and funding of subsequent deep and super cave projects.

The inclusion of secondary target mines is particularly relevant to interpreting the position of the Hugo North Lift 1 panels. Panel 0 has ramped up to >30 ktpd and is comparable in depth, production rate and mining reserve to Palabora Lift 1 and the Henderson 7,700 and 8,100 Levels. The similarity in scale highlights how performance metrics and operating experience from these smaller, deep caves can provide critical context for assessing HNL1 panel-scale behaviour within the broader envelope of documented caving experience. Figure 3 illustrates the relative footprint scale of HNL1 and P0 in comparison with selected benchmark caves.

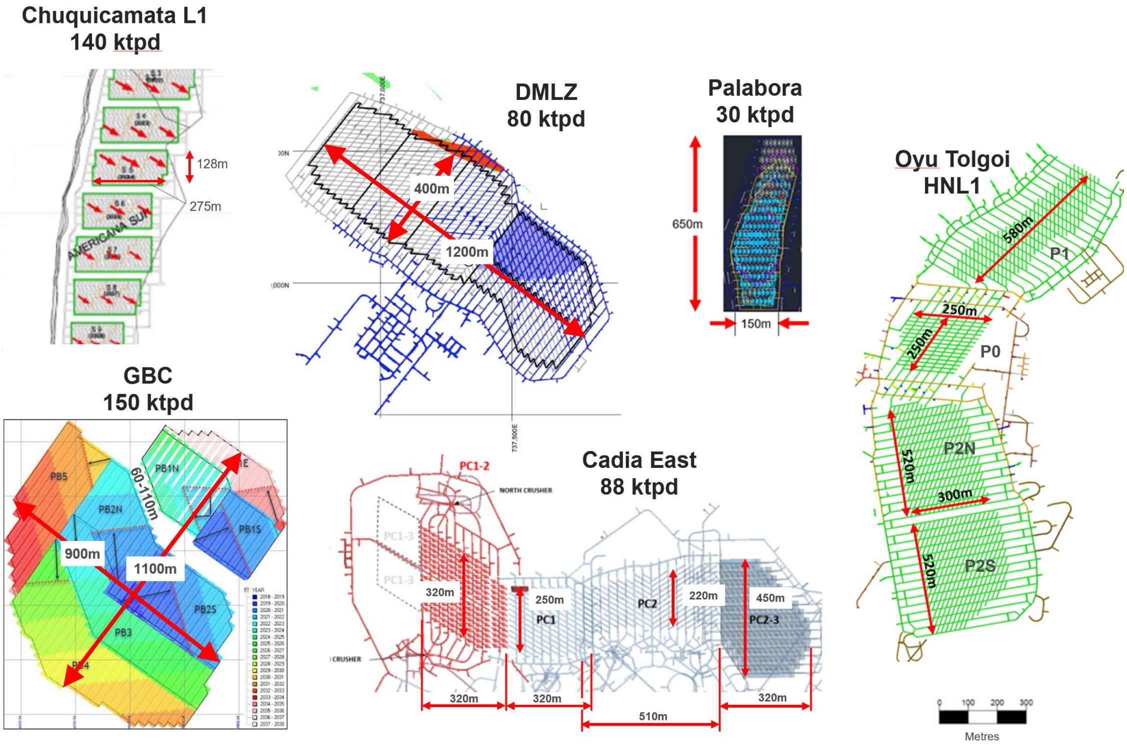


Figure 3 Cave footprint comparison of Grasberg's Deep Mill Level Zone (DMLZ) after Pierce et al. 2020, Grasberg Block Cave (GBC) after Beard & Brannon 2018, Palabora after Diering et al. 2018 and Oyu Tolgoi Hugo North Lift 1 (OT HNL1) after Ulziijargal et al. 2024

3 Benchmarking results and discussion

The benchmarking results provide a comparative view of cave depth, lift height, footprint scale and sustained production rates across a range of deep and super cave operations. The results are used to position HNL1 and P0 within the envelope of documented deep and super cave experience. Key trends, limitations and contextual factors influencing interpretation of the benchmarked data are noted below.

3.1 Data limitations

The cautions that accompany the benchmarked data and graphs in this paper are numerous and obvious. Limitations with the benchmarked data and results include:

- Only public data is used.
- Available data is often conflicting or unverifiable.
- The desired metric may be unavailable, so interpretation is required. This can introduce subjectivity through interpretation.
- Site conditions differ significantly. Site-specific geographical, geotechnical and operational factors and constraints can significantly affect the benchmarked metrics. Knowing the context is critical.
- Reliability of a given data metric can vary across different sites and reporting periods.

3.2 Public caving data

Publicly available data was generally sufficient to benchmark first-order parameters such as cave depth, lift height, footprint scale and peak production rate (shown in Table 1). However, these headline metrics alone do not explain the underlying reasons behind the variations in ramp-up performance, production stability or long-term cave outcomes.

Table 1 Benchmarked cave data

	Mine	Cave	Ore handling	Peak production (ktpd)	Reserve (Mt)	Cave footprint metrics (in metres)					Lift no	Undercut type	Drive spacing		Drawpoint layout
						Length	Width	Area (m²)	Depth	Block height			DBL	XDr	
Super Caves	Oyu Tolgoi	HNL1	Shaft->conveyor	95	440	2,000	300	567,000	1,300	500	1	Advance	18	30	El Teniente
	Freeport	DOZ	Conveyor	50	374	600	1,000	600,000	1,150	350–500	2	Advance	17.3	30	El Teniente
	Freeport	DMLZ	Conveyor	80	439	1,200	400	480,000	1,700	325–550	3	Advance	20	30	El Teniente
	Freeport	GBC	Conveyor	160	936	1,100	1,100	588,000	1,235	190–550	1 (pit)	Advance	20	30	El Teniente
	Freeport	Kucing Liar	Conveyor	90	385	1,800	500		1,400	500–600	1	Advance	20	30	El Teniente
	Chuquicamata	L1	Conveyor	140	1,760	3,000	500	~35,000/mb	1,316	216–400	1 (pit)	Post	16	32	El Teniente
	El Teniente	New Mine Level	Conveyor	140	2,020			2,045,000	1,080	350		Advance	22	34	El Teniente
	El Teniente	Diamante	Conveyor	35					~650	~200		Post	20	34	El Teniente
	El Teniente	Esmeralda	Rail	45				188,400	730	140		Post->Adv	20	30	El Teniente
	Cadia East	PC1	Conveyor	43		320	250	73,000	1,225	1,225	1	Post	20	32	El Teniente
	Cadia East	PC2	Conveyor	80	1,300	510	210	116,000	1,425	1,425	1	Post->Adv	20	32	El Teniente
	Cadia East	PC1-2	Conveyor	42		320	320	116,000	1,225	1,225	1	Advance	20	32	El Teniente
	Cadia East	PC2-3	Conveyor	41		320	450	126,000	1,425	850	1	Post	20	32	El Teniente
Single Caves	Ridgeway Deeps	L1	Conveyor	20	101	400	250	100,000	1,114	224	2 (SLC)	Advance	18	30	Herringbone
	Palabora	L1	Shaft	33	220	650	250	162,500	1,200	400	1 (pit)	Advance	18	34	Herringbone
	Palabora	L2	Shaft	32		650	250	117,000	1,650	450	2	Advance	18	34	Herringbone
	Northparkes	E48	Shaft	15	56	300	180	54,000	580	580	1	Advance	18	30	Herringbone
	Northparkes	E26 L1	Shaft	11	44	196	180		480	390	1 (pit)	Advance	16	36	Herringbone
	Northparkes	E26 L2	Shaft	12.5		180	180	32,400	835	350	2	Advance	18	30	Herringbone
	Northparkes	E26 L2N	Shaft	12.5		180	90	16,200	835	350	2	Advance	18	30	Herringbone
	Finsch	B4	Shaft	16	24	300	400	120,000	630	120		Post	15	30	Herringbone
	Cullinan	CC1	Shaft	16	39			57,000	839	194		Advance	21	32	El Teniente
	New Afton	B1 B2	Conveyor	14.4		550	130	66,600	615	350	1	Advance	15	18	El Teniente
	New Afton	B3	Conveyor	11		210	110	23,000	775	160	2	Advance	18	28	El Teniente
	New Afton	C	Conveyor	14.5	27	100	430	43,000	1,165	390	3	Advance	18	28	El Teniente
	Argyle		Conveyor	18	49	500	240	75,000	800	250	1 (pit)	Advance	16	30	Herringbone

3.3 Deeper, taller caves

Cave depth and cave (i.e. lift) height were key metrics that were benchmarked. Cave height is a proxy for production rate, since lifts < 300 m in height will struggle to produce 80 ktpd unless numerous caving fronts, production panels or multiple mines (e.g. El Teniente) are active simultaneously. Variations in the type of overlying material were also noted to capture whether the cave moved upwards into overlying cave lifts, old workings or open pits, or through intact rock to surface breakthrough. The benchmarked cave depth and lift height information is shown in Figure 4.

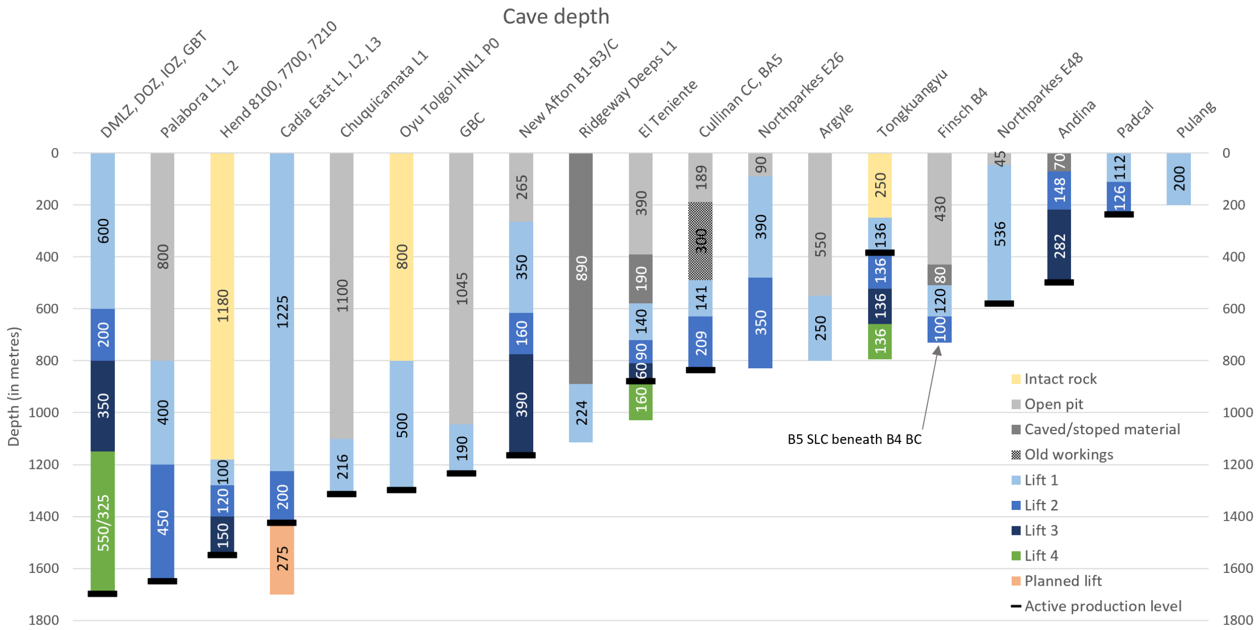


Figure 4 Benchmarked cave depth and lift height information

In the 1970s Henderson led the industry with the 8,100 Level cave, with the extraction level at a depth of 1,280 m. The second lift at Henderson, the 7,700 Level, began in 1992 at a depth of 1,400 m (Shea et al. 2018). Palabora Lift 1 started in 2000 at a depth of 1,200 m below surface and 400 m below the floor of the overlying open pit (Paetzold et al. 2020). Freeport's DMLZ cave, the third lift, underlies DOZ and IOZ (Intermediate Ore Zone) caves, and is 1,500–1,800 m deep (Simanjuntak et al. 2020). Henderson 7,210 Level set the depth record for a block cave when it started production in 2005 with the extraction level at 1,550 m below the peak of Red Mountain (Callahan & Gillon 2012). This depth has since been surpassed by DMLZ at a variable depth of around 1,700 m and Palabora Lift 2 at a depth of 1,650 m (Paetzold et al. 2020).

Comparing the Henderson 8,100 Level and Palabora Lift 1 caves raises two separate benchmarking depth metrics for comparison – depth of the cave below surface and cave height (e.g. the distance between the extraction level and breakthrough to the ground surface or pit floor, or into overlying workings. Lift (or draw) height refers to the column height of ore above the extraction level and is the in situ orebody height that is forecast to be drawn through the drawpoint (i.e. as ore, versus caved waste material overlying the orebody). Cave height, cave depth and lift height are all measured from the extraction level.

At both Freeport and Henderson, mountainous and highly variable topography makes prescribing a definitive depth difficult as the thickness of overlying rock varies significantly across the cave footprint. This results in several different depths being cited in the public domain. The mountainous terrain above DMLZ means that it is operating at levels 1,500–1,800 m below ground surface due to varying surface topography (Simanjuntak et al. 2020).

The extraction level of the HNL1 caves is 1,300 m below surface. Only 3 caves have been previously extracted at a similar depth and caved through to surface – Henderson 8,100 Level, and Cadia East PC1 and PC2 caves, have all caved 1,200-1,400 m to breakthrough at surface. While other caves have been established at greater depths, they have significantly shorter cave heights and lie (at least in part) under existing caves or open pits (e.g. Henderson 7,700 and 7,210 Levels, Palabora Lift 2, Grasberg DMLZ and GBC, Chuquicamata Lift 1 and New Afton C–Zone). HNL 1 has an average lift height of 400 m and is overlain by ~900 m of waste (Ulziijargal et al. 2024), which is similar to DOZ, DMLZ, Northparkes E48, and Palabora Lift 1 and 2. This places HNL1 lift height within the experience envelope defined by DOZ, DMLZ, E48 and Palabora.

Henderson's deep cave experience comes with the caution that molybdenite has lubricant qualities similar to those of graphite, and the molybdenite lamellae readily slide across each other and shear under very low forces. So while the depth of the Henderson 8,100 Level cave is readily comparable to P0 at Oyu Tolgoi, the rock mass properties and caveability of the rock masses differ significantly.

With the step change in lift height and cave depths, the next step is to examine how these geometries translate to sustained production rates despite the geotechnical impacts of operating at greater depths.

3.4 Production rate

Freeport's DOZ cave was the first super cave, achieving sustained maximum production of 80 ktpd in 2010 and 2011. The first cohort of super caves behind DOZ remains an exclusive group consisting of Cadia East PC1 and PC2, DMLZ and GBC. This exclusivity necessitated the inclusion of secondary targets for the study, focusing on smaller caves of comparable scale and depth to P0.

DOZ was originally designed to achieve a maximum production of 25 ktpd but production was steadily increased, initially to 35 ktpd, then 50 ktpd and finally to 80 ktpd from a single production block (Casten et al. 2020). The increase in production rate was driven, at least in part, by the near threefold increase in reserves from an initial pre-mining reserve of 96 Mt up to 283 Mt by 2008. DOZ went on to achieve the revised nameplate 80 ktpd production rate in 2008, more than 10 years before the next super cave. Strikes and export restrictions heavily impacted DOZ production after 2011 and resulting production delays lead to wet muck issues, extraction level damage and significant drive convergence (Casten et al. 2020). Since 2011, DOZ was only able to sustain production rates of around 50 ktpd.

The first block cave at Cadia East, PC1, began producing in 2013 and production from the neighbouring, deeper cave, PC2, commenced in 2014. Total Cadia East ore production continued to ramp-up, exceeding 70 ktpd in 2018. Cadia East was the first super cave to sustain an average production rate for more than two years. Freeport's DMLZ cave reached peak production in 2023 and Grasberg cave achieved nameplate production of 150 ktpd during ramping up in 2023, 21 years after initial access (Beard et al. 2024).

Cadia East, DMLZ and GBC were at full production in 2025, with HNL1, Chuquicamata Lift 1 and El Teniente NML/Andesita in ramp-up, and Kucing Liar (Grasberg) in development, with a first production forecast for 2028 ramping up to full production (90 ktpd) in 2033 (Beard et al. 2024). However, all 3 operating super caves have experienced sudden, unplanned reduced output at various times. A fatal mud rush at GBC in September 2025 halted production, with ongoing disruption into 2026 (Freeport-McMoRan 2025a, b). At DMLZ in 2024, elevated seismicity and extensive drive damage necessitated the uplift of production block 4 (PB4), which re-sequenced and delayed access to several new caving fronts (Lolona et al. 2024). In April 2017 a large seismic event at Cadia East halted production from PC1 and PC2 for months and required extensive drive rehabilitation to regain access (Newcrest 2017). More recently, Cadia has faced fragmentation-related draw limits and temporary dust-related restrictions (Castro & Cuello 2018).

Chuquicamata Lift 1 is ramping up to peak production of 140 ktpd from 6 to 7 macroblocks. El Teniente's NML (Andesita, Andes Norte and Diamante) is in the early stages of development, 350 m below current caving operations, and will be El Teniente's first super cave. The first drawbell was fired in May 2025, with a planned 5-year ramp-up to ~35 ktpd and full production of 130 ktpd from NML scheduled in 2033 (Codelco 2025).

Figure 5 compares sustained rates across single block and multipanel operations, situating the HNL1 panels within the recent cave production envelope. The single caves with smaller footprints form the right-hand tail of the graph, leading to the multiple panel and super cave operations on the far left.

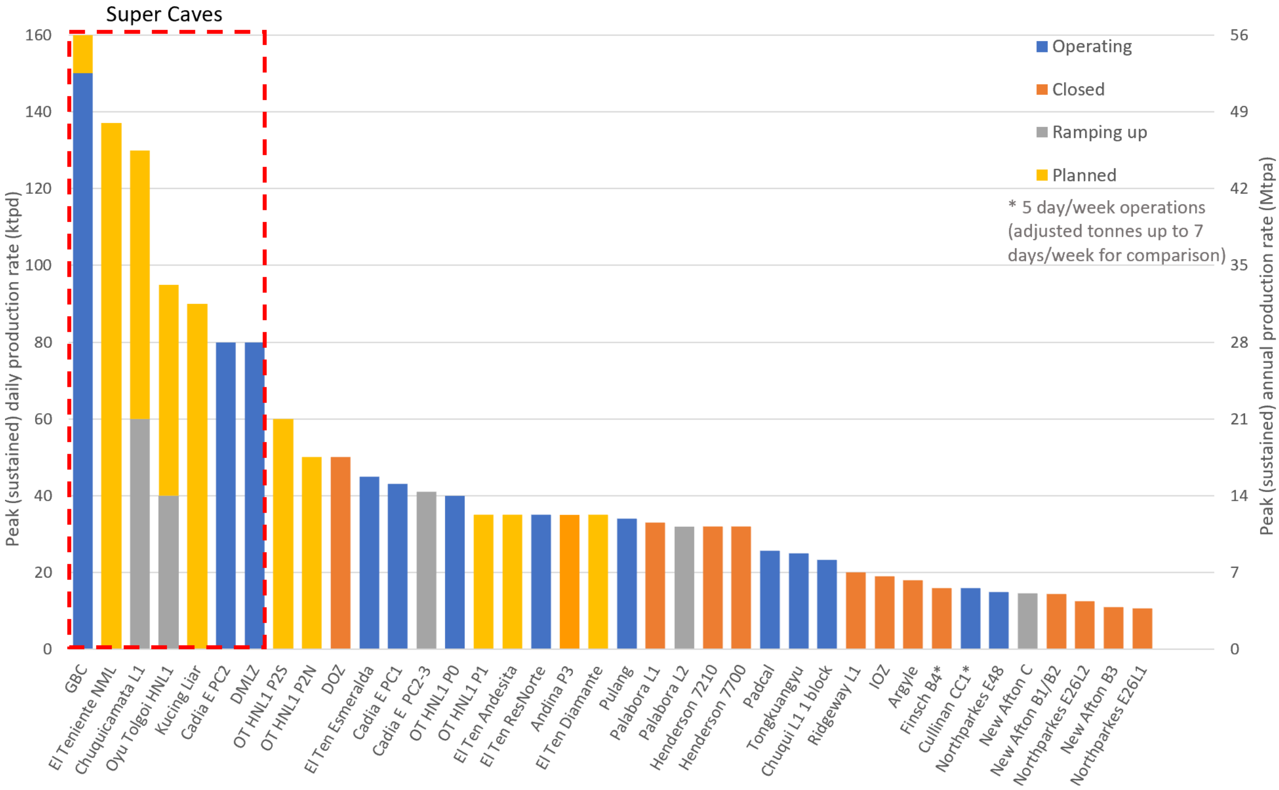


Figure 5 Peak (sustained) production rates

Cave depth verses production rate for various active and closed cave mines is shown in Figure 6. The graph captures public caving information, was initially compiled by Rio Tinto personnel and has been updated as a part of this benchmarking study.

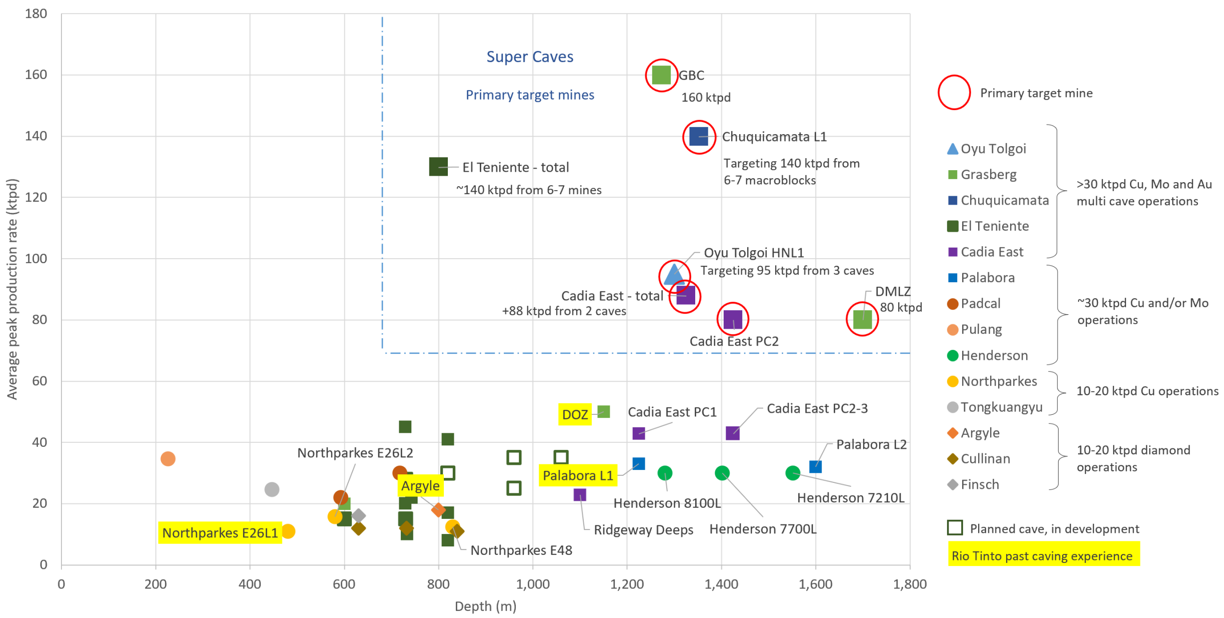


Figure 6 Comparing caving mines by production rate and depth below surface for active, closed and developing caves

To understand the footprint scale that enables the increased production rates, the pre-mining reserve was assessed as a proxy for total footprint and drawpoint inventory. Operational footprint details, and particularly drawpoint inventory (e.g. active, available, under repair, closed etc.) over time, are seldom available publicly, and for such large footprints the total number of drawpoints (which is often published) is not overly useful.

3.5 Pre-mining reserves

The pre-mining reserves of the target mines are plotted in Figure 7. Pre-mining reserves are a measure of cave scale and a proxy for total footprint area, block height or total number of drawpoints. Large operations run numerous panels, blocks or independent districts and, although details of the large reserves are typically readily available, information about the operation and nature of the sub-blocks and panels can be scarce. The benchmarking of the pre-mining reserve delivers a combined metric for total footprint and cave height but isn't especially useful at a deeper investigative level unless significantly more details are known, for example, number of active drawpoints and caving fronts (length, advance rate etc.). The design constraints, interactions and operation of the individual areas are not well-documented publicly and could not be adequately investigated in this benchmarking.

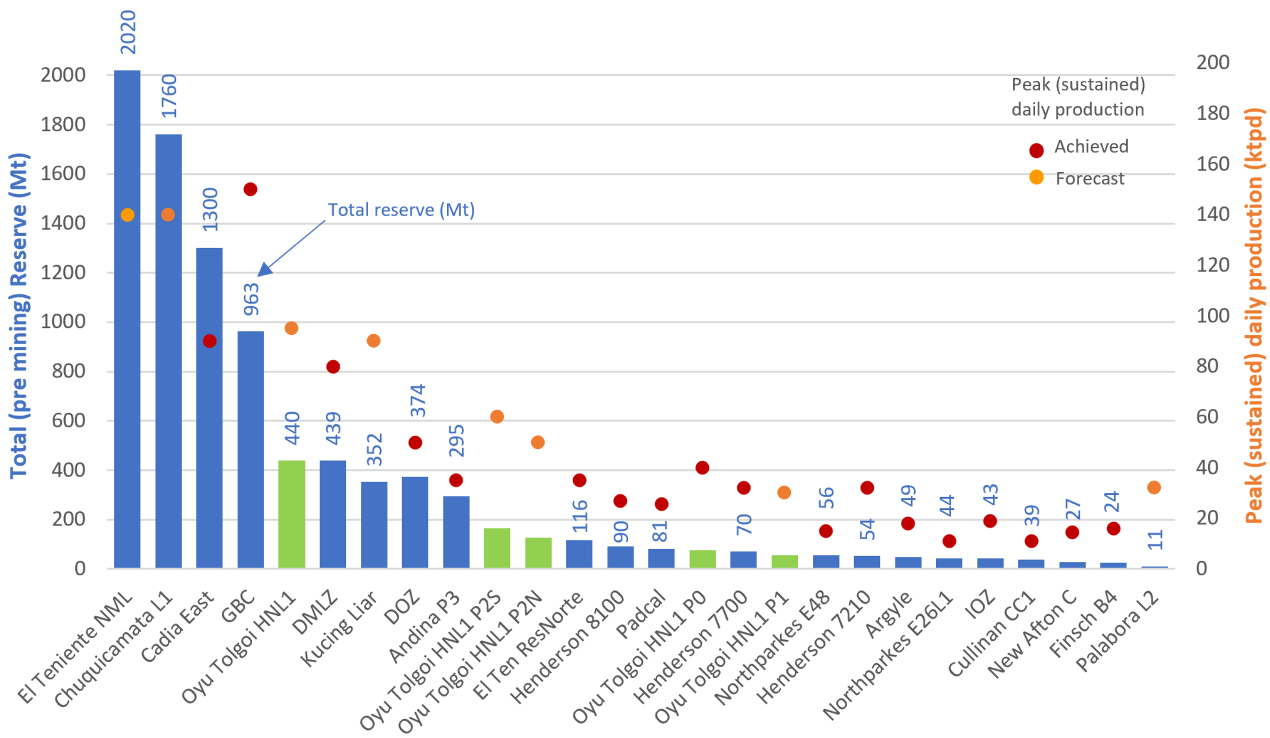


Figure 7 **Total (pre-mining) reserve and actual and forecast peak (sustained) daily production rate (Oyu Tolgoi Lift 1 shown in green)**

While comparing footprint and productivity scales between different caves was helpful in considering P0 and the whole of HNL1 (in Figures 5, 6 and 7), productivity and mining reserve are not the only factors driving a high, stable production rate; pillar behaviour and spacing on the extraction level are also critical.

3.6 Drawpoint spacing

Along with cave height and depth, drawpoint spacing has also increased significantly over the past 20 years. The increase in pillar size on the extraction level is not only a function of the increased extraction depth and in situ stresses. Ground conditions, fragmentation and seismicity are also critical factors for footprint stability, pillar behaviour and drive footprint design. The drawbell spacings reported for the benchmarked mines are shown in Figure 8. For several caves, the drawpoint spacing was increased for subsequent panels or even adjusted during panel development (e.g. New Afton B3, Cadia PC1 and PC2-3, and Cullinan CC1) in response to induced stress, seismicity and pillar performance.

An in-depth comparison of drawpoint spacing between caving operations would need to consider rock mass strength, structure and faulting, and in situ stress conditions. Ground conditions are critical to understanding the pillar strengths needed to produce stable, long-life pillars, prescribe ground support specifications, and estimate drawpoint life and rehabilitation requirements. The orientation of structures relative to the caving front, pillars, brows and undercut faces are also a critical consideration. This information is not publicly available at the necessary level of detail (e.g. variability across the footprint rather than a panel-wide average) and was not captured in this benchmarking.

Pillar size (due to the drawpoint and extraction drive spacing) will be a key driver in extraction level stability and drawpoint life, and, together with undercut strategy and development sequencing, can directly influence the pace and risk profile of the cave ramp-up.

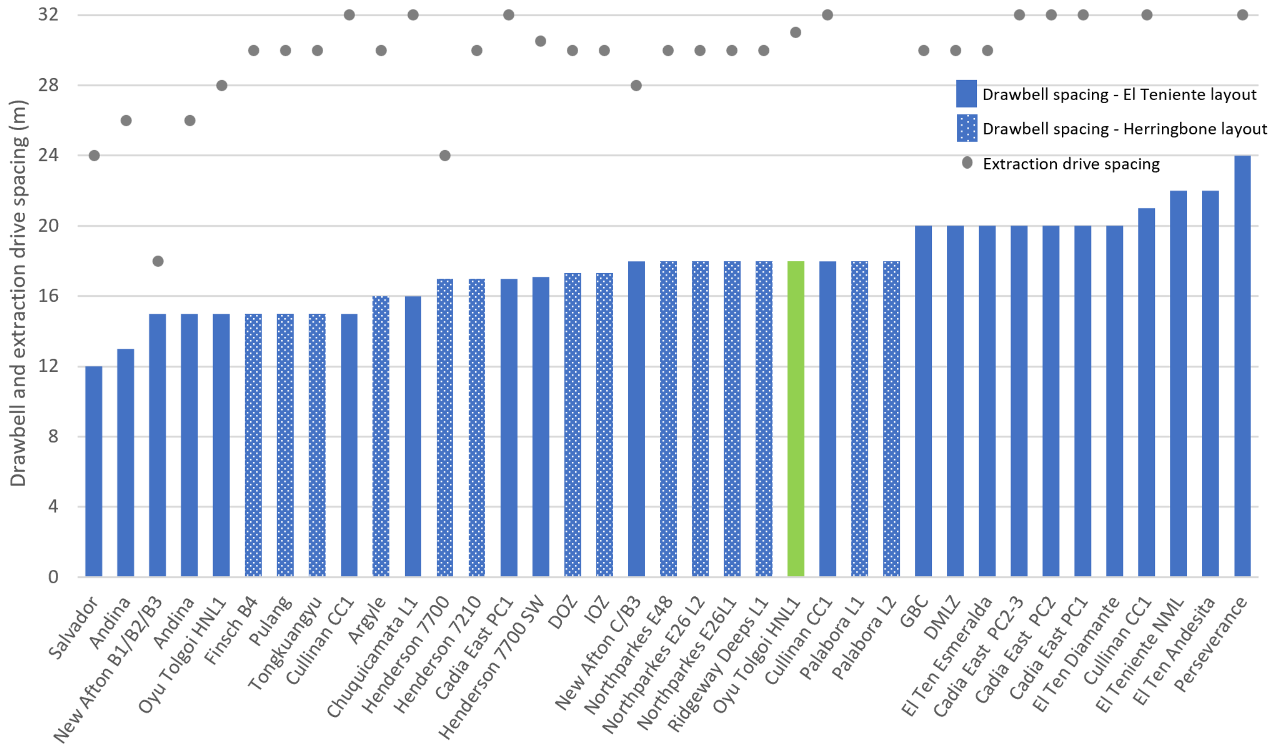


Figure 8 Drawbell and extraction drive spacing

3.7 Ramp-up rate

The rate and type of undercutting, number of undercutting or caving fronts, drawbell design and opening rate, and geotechnical factors, including structure and in situ stresses, all factor into ramp-up actuals. Understanding the causes and degree of variability of these factors across a footprint is key to building the context needed to undertake a meaningful comparison between caving operations. Interpreting ramp-up outcomes therefore requires explicit consideration of rock mass conditions, stress environment and seismic response.

A ramp-up duration is often forecast for feasibility studies; however, the underlying actual ramp-up rate and duration, including operational constraints and impacting factors, are rarely published. First drawbell or first undercut blast are the most common starting points in a ramp-up timeline, although any comparison needs to consider undercut strategy and the extent of pre-development. While there is public data on planned ramp-up rates for numerous caving operations, there is considerably less data on the actual achieved production ramp-up rates. Cadia East, Grasberg and New Afton document individual annual cave production actuals in the company reports and investor data, and their ramp-up rates are plotted in Figure 9. Palabora Lift 1 ramp-up actuals are also available.

Poor draw control and compliance are known to be key contributing factors to extraction level damage and production delays through pillar loading, drive convergence, rockburst, wet muck and dilution ingress. When comparing ramp-up rates, a faster ramp-up may not be the optimal economic outcome if it is achieved with poor draw compliance and delivers a legacy of ground damage, drive closures or dilution that impacts production rates and the value of the mining reserve.

Figure 9 summarises reported ramp-up trajectories but there is limited benefit in the graph as a standalone comparison unless the context and operational constraints behind rates for the sites are also known. If comparing ramp-up rates for similar caving heights, depths and production rates, then Oyu Tolgoi's ramp-up rate will be considered slow relative to Cadia and Grasberg. However, when the impact of having ore conveyors to surface is considered, Oyu Tolgoi's use of hoisting for the first 3 years of ramp-up, until the ore conveyor to surface was commissioned, completes the story and sets the basis for a well-grounded comparison.

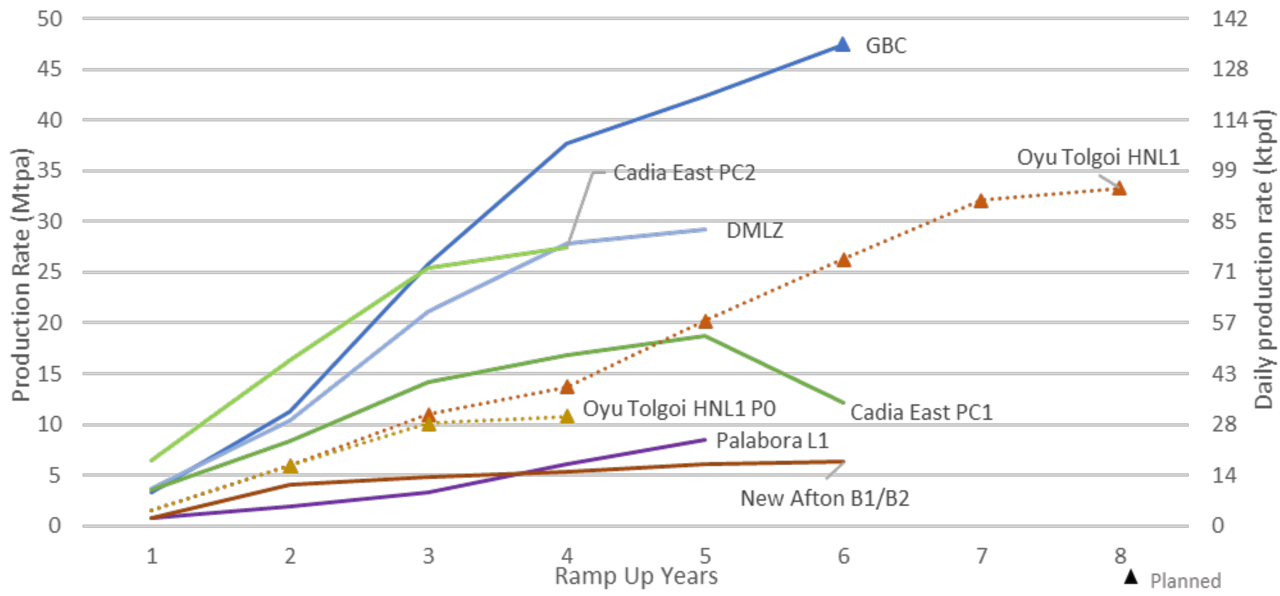


Figure 9 Reported actual ramp-up rates and Oyu Tolgoi's estimated ramp-up rate

3.8 Geotechnical considerations

Rock mass conditions are a critical consideration in cave design, performance and risk management. In situ and induced stresses are crucial to mine stability and cave propagation. Rock mass conditions, seismicity and stress were not benchmarked as the publicly available data was of insufficient detail to allow meaningful comparison between sites.

Seismic risks and hazards are key concerns in deep caving operations and benchmarking seismicity, rock mass strength and mining-induced stresses is a high priority. Seismicity and footprint stability are the key challenges that have delayed development and production at operating caving mines. The large caves studied have all experienced significant production impacts from the effects of seismicity, stress and collapses of ground, either during development or ramp-up, or at full production.

Significant seismic events that damaged development and impacted production rates have occurred at many of the large caves. At Cadia East, a rockburst event stopped PC1 and PC2 production for several months in 2017 (Newcrest 2017). DMLZ encountered higher-than-expected seismicity and undercutting was paused, which significantly delayed the planned production ramp-up (Casten et al. 2020). Several seismic events and rockbursts interrupted and delayed development of the conveyor belt tunnel, one of the main infrastructure access drives for Andes Norte (Rojas et al. 2023), and significantly delayed accessing El Teniente's NML.

Beyond seismicity, drive collapses and severe convergence, poor fragmentation, fines/dust and wet muck have caused production delays at several caving operations. Forced production limits at DOZ in 2011 led to extensive issues with wet muck, drive damage and convergence, which permanently impacted the future production rate (Casten et al. 2020). Collapses caused delays in ramp-up at Chuquicamata in 2023 (Cambero 2023). Production from Cadia East was heavily reduced in May 2023 to limit dust pollution while additional control equipment was installed (Cossins-Smith 2023). Public reporting of these issues has helped the industry learn and develop strategies and skills to reduce or manage these risks and hazards.

4 Data availability and benchmarking constraints

Despite the significant increase in cave scale, there has been limited systematic updating of global block cave benchmarks for several reasons. The population of caving cases is small, cave development and ramp-up time frames are long and public reporting of detailed operational data is frequently sparse, inconsistent or highly aggregated. The level of detail published varies between operations, reflecting differing reporting priorities and sensitivities. Collectively, these factors have constrained the availability of consistent, comparable data for benchmarking.

One of the key takeaways from this benchmarking is that limited caving data is publicly available from technical reports, company statements and published technical papers. While company reporting and numerous published papers are available for some caving operations, other caving operations rarely, or incompletely, publish caving metrics. Sites that opt for limited reporting make it difficult to understand the critical issues an operation is facing and hinder understanding of the similarities and relevance between caving operations.

Understanding the context and site-specific differences, and having consistent data for benchmarked caves, are critical to meaningful benchmarking and interpretation (Ross 2018). Materials handling, equipment capacities and degree of automation, undercut and extraction strategies, and operational constraints may be significant points of difference that influence the raw benchmarked metrics. A key priority in any side-by-side site study or comparison would be the comparison of mining-induced stresses and rock mass conditions.

To extend benchmarking beyond first-order comparisons of cave depth, lift height and nameplate production, and to meaningfully compare sites in terms of demonstrated experience and risk, more targeted and contextual data is needed. Benchmarking for future, deep and super cave projects would be improved with the inclusion of data capturing for:

- ramp-up constraints
- drawpoint performance, availability and life
- undercut front lengths, advance rates and sequencing
- geotechnical context (including structure, rock mass quality, stress and seismicity)
- materials handling and infrastructure constraints.

While acknowledging commercial sensitivities and site-specific complexity, more consistent reporting of these contextual parameters would significantly improve the industry's ability to benchmark large, deep block caves and to distinguish between design limits, operational constraints and geotechnical controls.

5 Conclusion

The benchmarking confirms a structural shift in cave depth, lift height and achievable production rates relative to pre-2003 ranges. Over the past 2 decades, block caving has progressed to significantly greater depths and taller cave columns, enabling step changes in production scale and mine design. Consequently, many cave metrics commonly referenced from the early 2000s benchmarking no longer reflect contemporary practice, particularly for deeper, higher-lift and higher-productivity caves. The transition from super cave projects to operating super caves has materially expanded the ranges of cave depth, column height, footprint scale and sustained production rates now demonstrated.

The benchmarking also shows that only a small number of super caves have operated at sustained peak production for extended periods, reinforcing the importance of drawing on experience from smaller, deep block caves. In this context, Hugo North Lift 1 – and particularly Panel 0 – sits well within the envelope of documented caving experience when assessed against cave depth, lift height and production rate.

Publicly available data is generally sufficient to benchmark first-order parameters; however, these headline metrics alone do not explain variations in ramp-up performance, production stability or long-term cave outcomes. Site-specific conditions and constraints, and differences in operating context, strongly influence results. A meaningful benchmarking comparison between operating caves requires information on cave geometry, sequencing, ramp-up strategy and operational constraints.

While recognising commercial sensitivities and the inherently site-specific nature of caving operations, greater consistency in reporting these contextual parameters would significantly strengthen benchmarking efforts. As new super caves advance through ramp-up, disciplined sharing of caving data and operating context will be increasingly important to refine the envelope of demonstrated experience for the next generation of super caves.

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Please note that this paper contains estimates, projections, and forward-looking statements within the meaning of applicable securities laws. These statements, including matters relating to production targets, ramp-up expectations and development schedules, are based on publicly available information, operational observations, assumptions and interpretations available at the time of writing. Actual outcomes may differ due to operational, geotechnical, market, regulatory and other factors.

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