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Tracking Grade Heterogeneity in a Panel Cave Mine: A Reconciliation Study Investigating the Impact of Mixing from an Ore Sorting Perspective

Mahir Can Cetin [1,*], Bern Klein [1], Genzhuang Li [1] and William Futcher [2]

[1] Norman B. Keevil Institute of Mining Engineering, University of British Columbia, Vancouver, BC V6T 1Z4, Canada; bklein@mining.ubc.ca (B.K.); genzhuang.li@ubc.ca (G.L.)
[2] Newcrest Mining Limited, Level 8, Melbourne, VIC 3004, Australia; william.futcher@newcrest.com.au
* Correspondence: mcetin@mail.ubc.ca

Abstract: Bulk ore sorting is a preconcentration method applied to bulk streams or batches of material. The effectiveness of bulk ore sorting relies on the degree of the naturally occurring in situ grade heterogeneity of an ore deposit. The blending of ore during mining and material handling degrades the in situ grade heterogeneity initially present in an orebody and reduces the potential to apply bulk ore sorting. Block and panel cave mines experience mixing from the establishment of caves to the delivery of the caved ore to concentrators. This study focused on tracking the grade heterogeneity and quantifying the impact of mixing on the sorting potential of the Cadia East panel cave mine via the reconciliation of the grade measurements performed at different locations. The results showed that the copper and gold grades were almost fully homogenized via various mixing events identified for the mine. The tracked grade heterogeneity values revealed that the mixing during material handling, which included ore blending according to mine planning, reduced the grade variability more drastically than the mixing within the caves. As the ore travelled from its original in situ location, the grade distributions gradually transformed, and the grades eventually normalized around the mean values. Only insignificant amounts of low-grade material that could have potentially been discarded were reported to the on-belt sensor located at the surface. The results of this study are significant for cave mines exploring sorting systems for preconcentration as they highlight how mixing can impact the variability in ore grades.

Keywords: block caving; panel caving; tracking heterogeneity; grade reconciliation; impact of mixing; bulk ore sorting

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1. Introduction

Sensor-based ore sorting is a method that involves identifying and discarding waste or uneconomic material using the information obtained by sensor technologies to improve the quality of processing plant feed. Numerous sorting studies carried out over the last decade have led to the recognition of the method as a standard tool for preconcentration, and an increasing number of mining projects have started to include sensor-based ore sorting in their flowsheet designs [1].

Bulk ore sorting is the name given to the method when applied to bulk streams or batches of material. Bulk ore sorting technologies can be mounted on conveyors or integrated with shovels or trucks for both ore-waste diversion and enhancing grade control decisions. Sensor technologies used for bulk ore sorting differ regarding the ability to perform penetrative or surface measurements [2,3]. Whether penetrative or surface-based, sensors should provide accurate and rapid grade information to enable increased selectivity while applying low-cost bulk mining methods. In addition to the sensors' measurement quality, the effectiveness of bulk ore sorting relies on the naturally occurring in situ grade heterogeneity of an ore deposit [2,4,5]. A wider distribution of in situ grades, i.e., higher heterogeneity, can mean a higher potential for discarding more waste or low-grade material using sensors and for applying preconcentration by bulk ore sorting.

Mixing occurring during various mining unit operations reduces the grade heterogeneity that initially existed in an orebody, which also reduces the potential to apply bulk ore sorting [6,7]. A particular focus of sensor-based ore sorting studies is cave mining operations since they experience ore mixing from the establishment of caves to the delivery of the caved ore to concentrators [8]. Caving is a non-selective mining method since recovered grades are a function of how the ore breaks, flows and mixes in draw columns before reporting to drawpoints [8,9]. Material handling processes for transferring the caved ore from drawpoints to surface stockpiles inevitably contribute to mixing, further reducing grade variability [8]. In addition, production schedules of many caving operations require the blending of ore collected from different drawpoints to reduce the fluctuations in the quality of mill feed [9,10] and prevent major hazards, such as air blasts, that may occur due to uncontrolled draw rate and sequence.

Studies assessing the degree of heterogeneity and the performance of bulk sensors are crucial for addressing the operational and technical uncertainties of bulk ore sorting. Deploying sensors on production conveyors or constructing offline testing facilities operating at near-production scales are the testing approaches adopted for brownfield operations [6]. The Cadia East panel cave mine presents a significant opportunity for tracking how the mixing events affect grade heterogeneity. The mine monitors the ore quality using two bulk ore sensing technologies: a prompt gamma neutron activation analysis (PGNAA) sensor of Scantech and a magnetic resonance (MR) sensor of Nextore. The sensors perform grade measurements on the main trunk belt conveying the ore from underground to the concentrators at a rate of 4600 tonnes per hour. PGNAA is a non-destructive and non-contact analytical technique that can penetrate the entire cross-section of conveyed flows to carry out real-time elemental composition measurements. PGNAA measurements can typically be 30 seconds, one minute, or two minutes long, and depending on the measurement time, PGNAA can measure copper to a precision of 0.02% copper [11]. The MR technology allows for the rapid quantification of mineral phases rather than elemental compositions to report the grade [12,13]. MR can measure copper at very low grades (a few hundred parts per million) by sensing certain copper minerals [13]. The MR sensor used at Cadia East has been tuned to detect only chalcopyrite over 30-second measurements, and it is likely to underestimate the copper grades since the technology cannot detect bornite, which is also present in the ore. Therefore, the multi-element information provided by the PGNAA sensor is more suitable for investigating the spatial change in grade heterogeneity.

This study aims to track grade heterogeneity and evaluate the impact of mixing from a bulk ore sorting perspective for the Cadia East panel cave mine. The block model, drawpoint sampling, and PGNAA sensor data sets were reconciled to demonstrate how the heterogeneity in copper and gold grades was altered by ore mixing as the ore was caved, handled underground, and then delivered to the surface. The theoretical recoveries and upgrading ratios of copper and gold and sorter mass rejection rates were calculated to reveal the impact of mixing within cave columns and along the material handling system on the potential to apply ore sorting. The results presented in this study offer valuable information to mining operations extracting similar ore types with block or panel caving methods in terms of how mixing impacts the preconcentration opportunity.

2. Identification of Mixing Events at the Cadia East Mine

Cadia East is a gold-copper panel cave mine located southwest of Orange, New South Wales, Australia. At the time of this study, the panel caves, referred to as PC1, PC2-West, and PC2-East, were in operation concurrently to produce gold doré and gold-rich copper concentrate in two concentrators with a total processing capacity of over 30 million tonnes per annum [14].

Figure 1 demonstrates a simplified diagram of the mining and material handling activities at Cadia East. As the mine applies the panel caving method, the Cadia East orebody is progressively undercut to propagate caving. The caved ore flows through drawbells to the drawpoints located on the extraction level. Load–haul–dump (LHD) units collect the caved ore from drawpoints and tip the ore into run-of-mine (ROM) ore bins feeding jaw-gyratory crushers. The crushed ore is subsequently passed to surge bins that provide material onto a series of collection conveyors. The main trunk belt fed by the collection conveyors transports the ore to the surface at a conveyance rate of 4600 tonnes per hour.

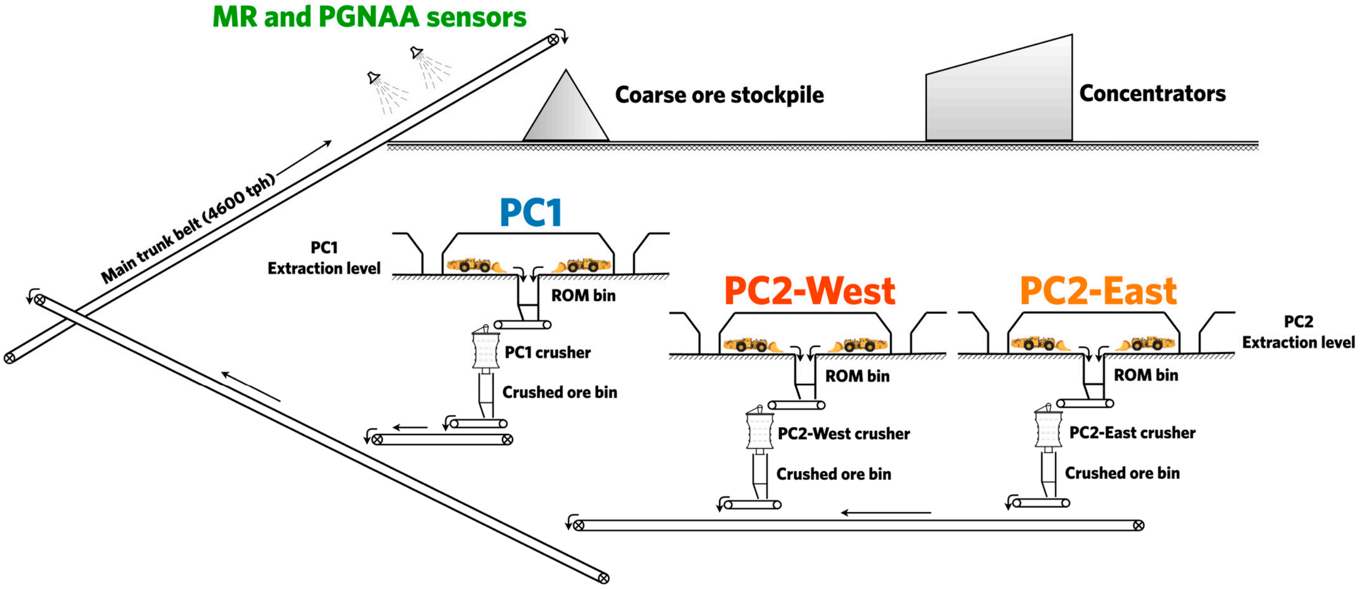


Figure 1. Simplified diagram of mining and material handling activities at the Cadia East mine. Arrows show the direction of material movement.

Various mixing events that can affect the grade heterogeneity and the bulk ore sorting potential of the Cadia East mine have been identified and are listed in Table 1. The mixing events shown in Table 1 include a series of mixing stages that occur due to the characteristics of the cave mining method. The collapsing of ore onto the caved ore muck pile and the flow of ore through draw columns are the mixing events occurring within the caves. These also include the lateral mixing (rilling) of ore and the potential introduction of fines from more mature PC1 into younger PC2-group caves. The draw sequence and subsequent blending of ore collected from different drawpoints to meet grade targets and manage the caves safely is the first mixing event occurring during material handling. Ore flow through the ROM and crushed ore bins and the mixing on the conveyor belt are the other mixing events along the material handling system.

Table 1. Mixing events that can affect the grade heterogeneity and bulk ore sorting potential at the Cadia East mine.

Mixing Location	Chronological Order	Ore Mixing Event
Within caves	1 2	Collapsing of ore onto caved ore muck pile as caving progresses Flow through draw columns
Material handling system	3 4 5 6	Blending according to mine planning to provide concentrators with consistent feed and manage panel caves safely Flow through ROM bins Flow through crushed ore bins Mixing of crushed ore originated from different panel caves on collection conveyor belts

3. Methodology

3.1. Investigation Period

An investigation period of two months, from the 1 April to 1 June 2019, was selected based on the reconcilable data obtained from the mine. Table 2 summarizes the key production figures targeted and achieved for the investigation period. A total of 423 drawpoints were in operation continuously to collect caved ore over a wide region of the cave footprints. The PC2-West and PC2-East caves were the source of most of the production, with a combined tonnage share of over 93% with a targeted average height of draw (HOD) values of 10.2 and 6.2 m, respectively. HOD measurements help determine the extent to which caved ore has been extracted or needs to be extracted. The PC1 cave was the most mature cave, with almost 44% of its footprint having already been extracted, with an average HOD of approximately 357 m. In contrast, the HOD values for the two-month period for the PC2-West and PC-East caves were 199 and 118 m, respectively.

Table 2. Production numbers at Cadia East between 1 April 2019 and 1 June 2019.

Panel Cave	**Active Drawpoints**	**Between 1 April 2019 and 1 June 2019**		**Until 1 April 2019**	
		Tonnage Share (%) of Caves	**Average HOD of Drawpoints Targeted**	**Tonnage Share (%) of Footprints Caved**	**Average HOD of Drawpoints Achieved**
PC1	127	6.55	1.33	43.88	357.15
PC2-West	129	51.78	10.15	15.81	199.12
PC2-East	167	41.66	6.16	10.7	118.11
Total	423	100	-	-	-

3.2. Data Description and Grade Reconciliation

The drill hole, drawpoint sampling, and PGNAA sensor grades were used in the study, and only the copper and gold heterogeneities were tracked spatially since these metals are the major drivers of the Cadia East mine's economics.

A block model of the Cadia East deposit that was previously built utilizing inverse distance weighting (IDW) was used to estimate the in situ copper and gold heterogeneities. The selected ore block size was $5 \times 5 \times 5$ m^3, which corresponded to 345 tonnes of ore. The in situ heterogeneity values were intended to be utilized as a point of reference for evaluating the impact of mixing within the caves and along the material handling system, as presented in Figure 2.

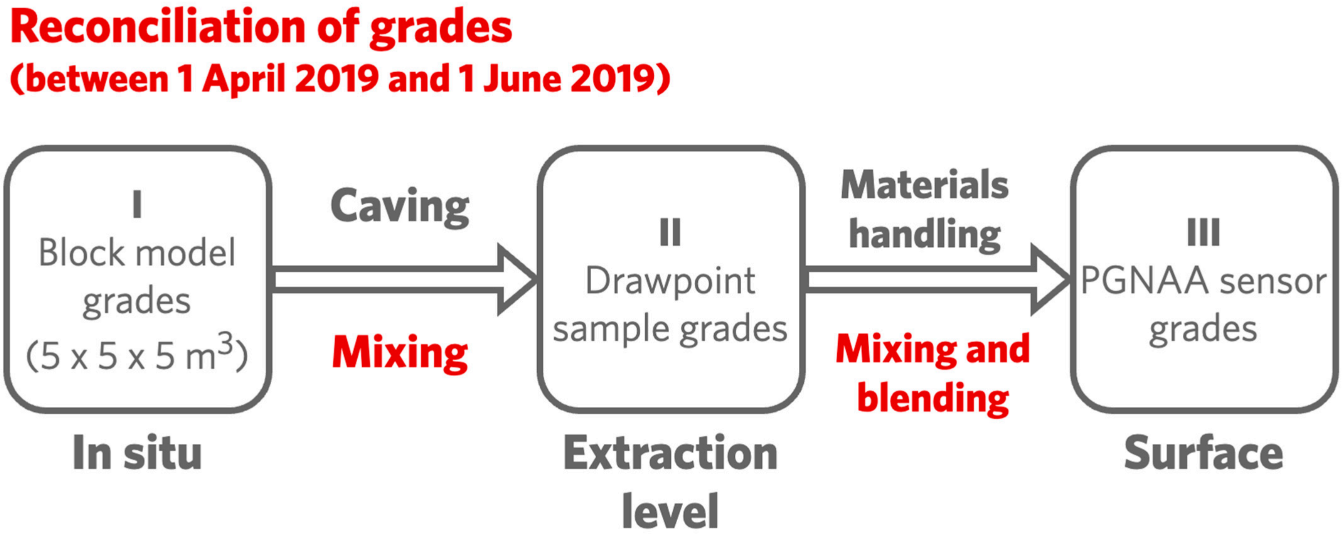
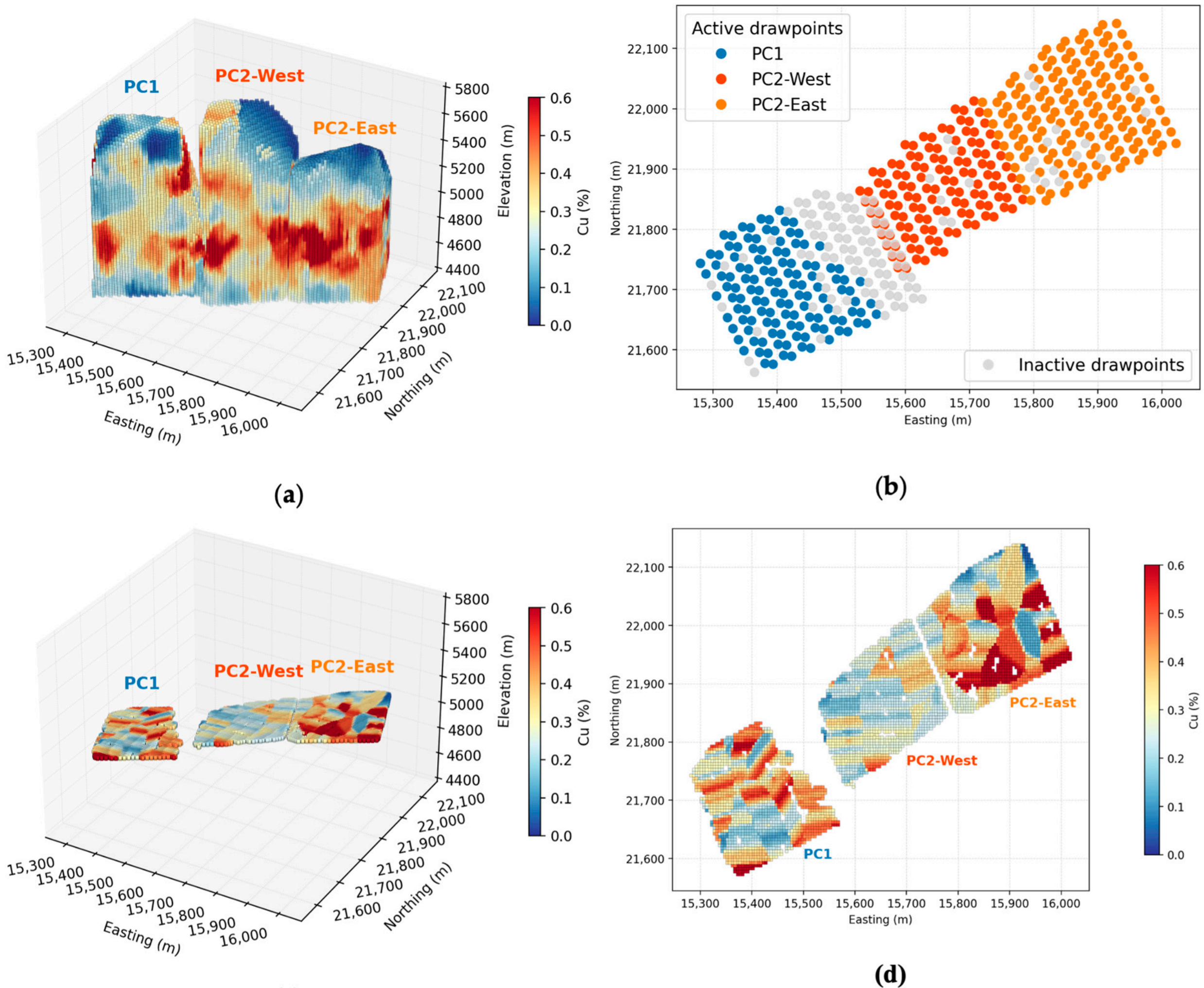


Figure 2. A simplified workflow of grade reconciliation.

A Python script package was created to select the ore blocks planned to be mined during the investigated period. The script was aimed at mimicking the slice file construction procedure of mine management and the planning software called Personal Computer Block Cave (PCBC), which was utilized for block and panel cave mines [15]. With the script, first, all the ore blocks that were planned to be caved over the life of the mine (LOM) were located. Second, the drawpoints that were active during the investigation period were determined. Third, considering the coordinates of the active drawpoints, the active draw columns were identified. A radius of 14 m for each draw column was used based on the interaction range of the neighbouring drawpoints reported for the Cadia East mine [14]. Fourth and finally, the ore blocks planned to be extracted during the two months were selected based on the coordinates of the identified draw columns and the height of draw (HOD) achieved for each drawpoint. It was ensured that the blocks were not selected twice due to the overlapping draw columns. The outcomes of the block selection procedure are shown in Figure 3.



(a) (b)

(c) (d)

Figure 3. Selecting ore blocks with the created Python script package: (**a**) ore blocks (5 × 5 × 5 m^3) planned to be caved over the life of the mine; (**b**) drawpoints operated during the investigation period; (**c**) ore blocks planned to be caved between 1 April 2019 and 1 June 2019—isometric view; and (**d**) ore blocks planned to be caved between 1 April 2019 and 1 June 2019—plan view.

Provided that the production is not impeded, the Cadia East drawpoints are sampled regularly, ideally once a week to monitor caved ore grades. The samples taken from at least three different locations of a drawpoint muck pile are collected in 5-kg bags after being screened using a 45-mm screen to exclude large particles [14]. The drawpoint samples are assayed for elements, including gold, copper, silver, and molybdenum, among others. The drawpoint samples' grades are compared with the milled grades and the grades forecasted by the cave planning and scheduling software. The production is reconciled to the orebody block model using the tonnages produced from each drawpoint, which is determined from the LHDs' bucket data. The grades of the drawpoint samples collected throughout the two-month period were used to calculate the heterogeneity at the extraction level and evaluate the degree of mixing occurring in the caves.

Figure 4 presents the daily average of copper and gold grades measured by the PGNAA sensor between 1 April 2019 and 1 June 2019. The PGNAA sensor employed at Cadia East carries out measurements at 2-minute intervals, corresponding to approximately 150-tonne ore pods, which is half the size of a block in the block model. The sensor reports the grades of various elements, including copper, gold, sulphur, and iron, among others. Although copper is measured directly by the sensor, gold is measured indirectly using a sensor algorithm, which may not always achieve accurate results. The tonnages of ore pods that the PGNAA sensor scans are determined by the belt weightometers and converted into dry tonnes using the moisture content information provided by an on-belt moisture analyzer. The sensor grade measurements performed during the investigation period were utilized in this study to estimate the heterogeneity at the surface and the degree of mixing taking place during the handling of the Cadia ore.

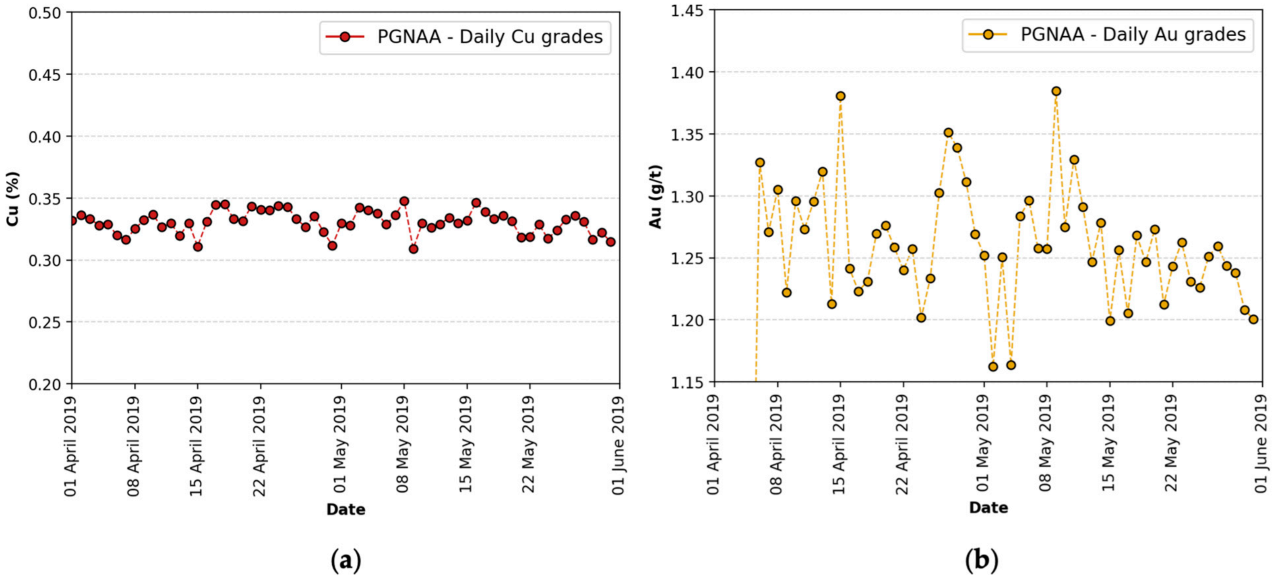


Figure 4. Daily grades reported by PGNAA between 1 April 2019 and 1 June 2019: (**a**) copper; (**b**) gold.

Table 3 presents the average copper and gold grades determined from the block model, drawpoint sampling, and PGNAA sensor data sets. The mixing and gravity flow occurring during caving is a dynamic process. The drawpoint sample grades used in this chapter might not fully represent the grades of the ore blocks planned to be mined during the investigation period. The ore reported to the drawpoints might originate from the other parts of the orebody, considering that the caves have been in production for several years and the possible lateral movement of ore and fines percolation occurring in the cave. In addition, the drawpoint samples may not be entirely representative of the drawpoint muck piles considering the challenges involved in the sampling of drawpoints. Similarly, the block model grades may not reveal the in situ heterogeneity due to the geostatistical interpolation smoothing out the ore grades. In addition, the grades reported by the PGNAA sensor might not be able to show the actual heterogeneity at the surface. The grade measuring algorithm of the sensor might have been developed in a manner to limit the prediction variance. Regardless, the copper and gold grades of the panel caves aligned well, which can suggest the validity of the grade reconciliation. Table 3 also shows that a reasonably high-grade portion of the deposit with average grades of 0.33–0.36% Cu and 1.16–1.21 g/t Au was extracted from the mine during the two-month period.

Table 3. Average copper and gold grades determined from block model, drawpoint sampling, and PGNAA sensor data sets.

Location	Panel Cave	Cu (%)	Au (g/t)
In situ (block model)	PC1	0.32	0.64
	PC2-West	0.35	1.30
	PC2-East	0.39	1.12
	All caves	0.36	1.18
Extraction level (drawpoint sampling)	PC1	0.36	0.57
	PC2-West	0.33	1.24
	PC2-East	0.38	1.20
	All caves	0.35	1.16
Surface (PGNAA sensor)	All caves	0.33	1.21

3.3. Assessing Impact of Mixing on Grade Heterogeneity and Bulk Ore Sorting Potential

Distributional heterogeneity (DH) and weighted variance (s_w^2) were the measures utilized to calculate the copper and gold heterogeneities in situ, at the extraction level and at the surface. Although both DH and weighted variance consider sample weights (ore tonnages) to estimate the variability in grade, there is a marked difference between them.

Despite being developed initially for accurate sampling practice of particle or rock lots [16], DH has been adopted in bulk ore sorting studies to provide an early insight into bulk ore sorting potential [2,17]. In metal-focused sorting studies, DH indicates the variability of the metal contents per unit of mass or volume of mined material with respect to the mean metal content. DH is a scalar measure of heterogeneity and can be calculated using the following equation:

$$\mathrm{DH} = \mathrm{N_u}\sum_{\mathrm{i}}\left[\frac{(\mathrm{a_i} - \mathrm{a_L})\mathrm{M_i}}{\mathrm{a_L}\mathrm{M_L}}\right]^2 \tag{1}$$

In contrast, the weighted variance shows the degree of variation within the metal grades, not metal contents, of individual ore groups making up a lot representing a unit mass or volume. Unit weights are factored in the weighted variance calculations since the calculations are performed around the weighted mean to measure the extent of the spread. The weighted variance is computed using the following equation:

$$\mathrm{s_w^2} = \frac{\mathrm{N'}}{\mathrm{N'} - 1}\frac{\sum_{\mathrm{i}}\mathrm{w_i}\left(\mathrm{x_i} - \bar{\mathrm{x}}_{\mathrm{w}}\right)^2}{\sum_{\mathrm{i}}\mathrm{w_i}} \tag{2}$$

Table 4 describes the variable used in Equations (1) and (2) to calculate DH and weighted variance, respectively.

The impact of mixing on the grade variability was also investigated by comparing the grade distributions determined from the block model, drawpoint sample, and sensor data sets. The theoretical probability distributions listed in Table 5 were tested by the least squares method to find the best fit for each data set. The change in the shape of the grade distributions was inspected via the parameters of the best-fit probability distribution functions.

Table 4. Variables used in DH and weighted variance calculations.

Variables	Location		
	In Situ	**Extraction Level**	**Surface**
N_u or N'	Number of ore blocks	Number of drawpoint samples	Number of ore pods scanned by PGNAA
a_i or x_i	Grade of a block	Grade of a drawpoint sample taken during a sampling period	Grade of an ore pod
M_i or w_i	Mass of a block	Total mass produced from a drawpoint during a sampling period	Mass of an ore pod
a_L or $\bar{x}_w$	Average grade of blocks	Average grade of drawpoint samples	Average grade of ore pods
M_L or $\sum_i w_i$	Total mass of blocks	Total mass produced from drawpoints	Total mass of ore pods

Table 5. Probability distributions fitted to data sets.

Distribution	Explanation
Burr	The Burr distribution was introduced by Burr [18] and can fit almost any unimodal data since it can yield a wide range of skewness and kurtosis values [19].
Chi-squared Erlang Exponential Gamma	Many variables in earth science are non-negative and positively (right) skewed [20]. The gamma distribution is a two-parameter distribution widely used for modelling positively skewed data. Chi-squared, Erlang, and exponential distributions are special cases of the gamma distribution.
Lognormal	The lognormal distribution has been determined to represent the frequencies of metal contents well when the ore deposit is modelled with consistent geologic settings, and the model data comes from well-explored deposits with spatial rules consistently applied [21].
Normal	The sample value frequency distributions of most mineral deposits commonly conform to the normal (Gaussian) or lognormal distributions [22].
Student's t	The student's t distribution is similar to the standardized normal distribution with heavier tails, meaning that it possesses a higher probability in the extreme values, or tails, compared to the normal distribution.

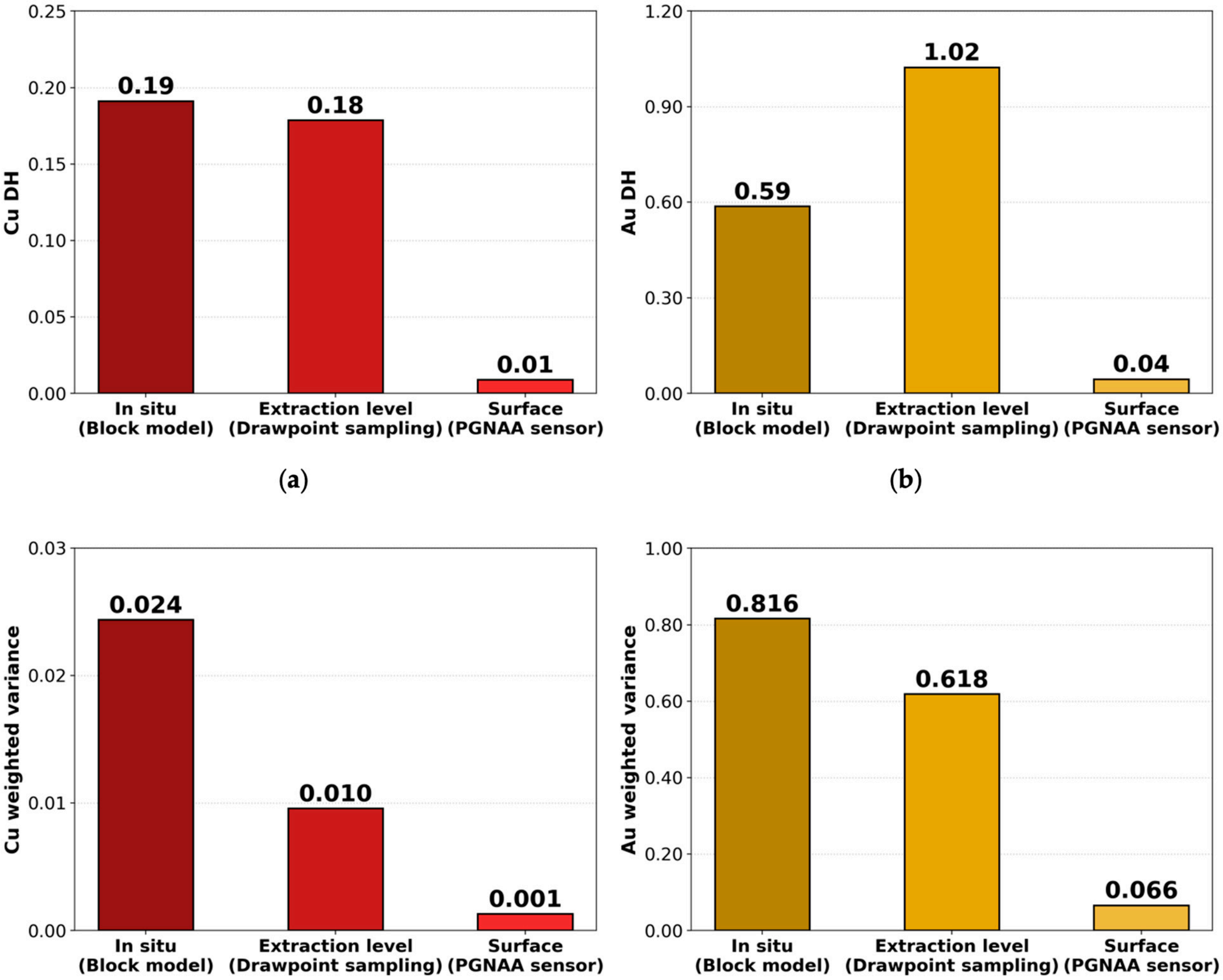
The potential to apply bulk ore sorting relies on the optimal recovery of the property of interest (e.g., copper or gold content) at the maximum mass rejection rate possible. The method offers higher mill feed grades while essentially reducing the overall processing expense by discarding low-grade or barren material. In addition, enhancing the ore quality via ore sorting may achieve higher metal recoveries at processing plants.

The Cadia East mine uses a Net Smelter Return (NSR) value of AUD18.71 (USD14.97 using an exchange rate of 1:0.8) per tonne ore as the mining cut-off threshold [14]. The use of an NSR value rather than a metal grade as the cut-off criteria is because the mine economics is driven by multiple commodities, copper, gold, silver, and molybdenum. Sorting cut-off grades of 0.1%, 0.15%, and 0.2% Cu were used in this study to determine the theoretical recoveries, upgrading ratios, and mass rejection rates that could be achieved by bulk ore sorting. Choosing copper as the sorting proxy element was due to copper's association with gold in the chalcopyrite and bornite minerals in the ore [23,24], as well as the consideration of the difficulties in accurately detecting the gold grade over short timeframes by the currently available bulk sensor technologies. The change in the sorting recoveries, upgrading ratios, and mass rejection rates were compared spatially to demonstrate the effect of mixing in terms of the decrease in the bulk ore sorting potential.

4. Results and Discussion

4.1. Impact on Grade Heterogeneity

The copper and gold DH values and weighted variances of the Cadia East ore calculated using the block model, drawpoint sample, and PGNAA sensor grades are presented in Figure 5. The in situ DH values and variances reveal that the ore extracted from the caves during the two-month period was relatively homogeneous but possessed grade variability to a certain extent. This suggestion was made based on the results of a study conducted by the authors [25], where the DH values of the entire footprints of the panel caves were estimated to be comparatively higher (DH values of up to 0.39 for Cu and 1.38 for Au) than the ones presented in Figure 5 (DH values of 0.19 for Cu and 0.59 for Au). Regardless, extremely low variability values estimated for the ore reported to the PGNAA sensor reveal that the ore grades were almost entirely homogenized due to ore mixing.



(**a**) (**b**)

(**c**) (**d**)

Figure 5. Distributional heterogeneity and weighted variances measured at three different locations, represented by the shades of red and gold colours: (**a**) copper DH; (**b**) gold DH; (**c**) copper weighted variance; and (**d**) gold weighted variance.

As previously discussed, mixing occurs within the cave columns during caving and along the material handling system during ore handling. When a comparison is made between the weighted variances shown in Figure 5c,d, it is observed that the mixing during ore handling reduced the variability more drastically. As presented in Table 6, the variances at the extraction level decreased by 61% for copper and 24% for gold in relation to the in situ variances due to the mixing in cave columns. In contrast, the variability declined more substantially, with 87% for copper and 89% for gold from the extraction level to the surface due to the mixing during ore handling.

Table 6. Percent change in the grade variation spatially estimated by the DH and weighted variance equations.

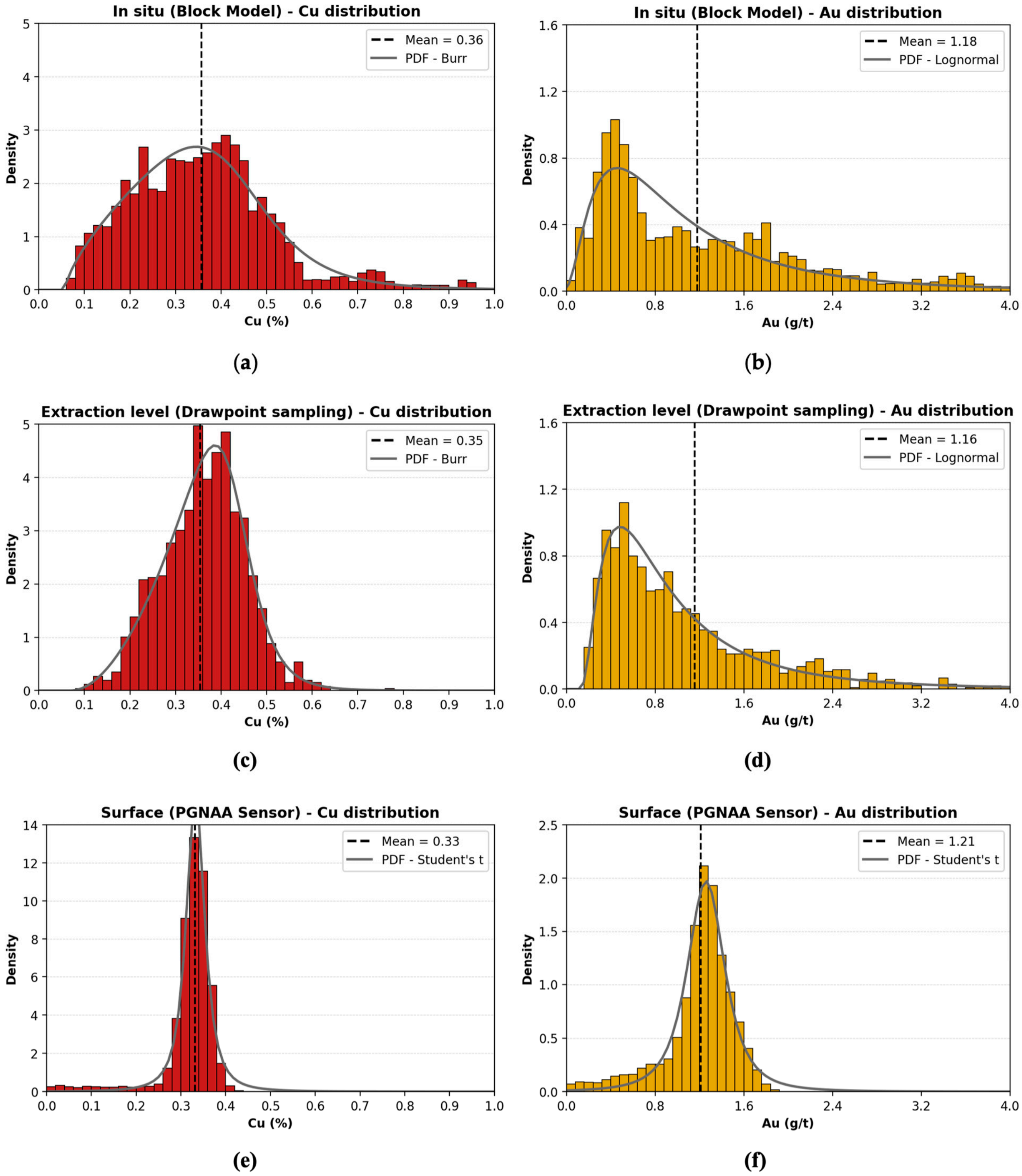
Location	Change (%) in DH and Weighted Variance Spatially			
	Cu		Au	
	DH	Weighted Variance	DH	Weighted Variance
In situ to extraction level	−7	−61	74	−24
Extraction level to surface	−95	−87	−96	−89
In situ to surface	−95	−95	−92	−92

The DH equation produced grade variability estimates that are not fully parallel to those obtained by the weighted variance equation. Considerably higher DH values obtained using the drawpoint samples suggest that the heterogeneity at the extraction level was preserved for copper and even increased for gold despite the mixing events occurring in the caves (Figure 5a,b and Table 6). The discrepancy between the variability estimates of DH and those of the weighted variance equation originates from the tendency of the former to be affected not only by the variability in grades but also by the variability in sampling frequency. Due to the concerns relating to maintaining production rates and likely underground hazards, the sampling frequency may be irregular at times in caving operations [26]. Such irregularity in the drawpoint sampling frequency of the Cadia East ore during the investigation period led to uneven tonnage intervals between the samples taken from each drawpoint. As the DH equation considered the drawpoint tonnages to indicate the degree of variability at the extraction level, it produced unrealistically high heterogeneity estimates.

In contrast, both equations yielded the same numbers (95% for copper and 92% for gold) for the overall change in the grade variability from the in situ location to the surface (Table 6). This was due to the tonnages of the ore pods that the PGNAA sensor scanned did not vary significantly over time. Therefore, it can be suggested that for ore lots with highly varying weights, the weighted variance equation can yield more reliable grade variability estimates than those obtained with the DH equation.

Overall, even though the processing plant received a consistent feed, as evident from the extremely low variability values estimated using sensor grades, the grade heterogeneity that initially existed in the ore blocks was lost due mainly to the mixing that occurred during material handling. It should be noted that blending the ore advertently to achieve consistent mill feed grades and preventing hazards was recognized as the first mixing event of material handling. Ore blending according to mine planning can be suggested as the mixing event where the heterogeneity is impacted the most since the mixing in ROM and crushed ore bins and on the conveyors is not as intense.

To further discuss the change in the grade variability, the grade distributions determined from the block model, drawpoint sampling, and sensor data sets are presented by a series of histograms in Figure 6. The parameters of the best-fit probability distribution functions, as determined using SciPy (an open-source Python library), are shown in Table 7. The Burr and log-normal distributions were determined to fit the in situ copper and gold grades best, respectively (Figure 6a,b). The mixing in the cave columns did not alter the metal distribution types; however, it led to narrower distributions at the extraction level (Figure 6c,d). The decrease in the spread can also be observed quantitatively by the change in the values of the scale parameters of the probability distribution functions determined using the copper and gold grades at the extraction level (Table 7). As the ore was blended underground and then transported from the extraction level to the surface, the grade distributions altered entirely, and the grades eventually normalized around the mean values (Figure 6e,f). The Student's t distribution, which shares similarities with the normal distribution, was determined to fit PGNAA's copper and gold grades.



(a) (b) (c) (d) (e) (f)

Figure 6. Grade distributions determined from block model, drawpoint sampling, and PGNAA sensor data sets (PDF denoting probability density function; red and gold colours represent copper and gold, respectively): (**a**) block model copper; (**b**) block model gold; (**c**) drawpoint sampling copper; (**d**) drawpoint sampling gold; (**e**) PGNAA sensor copper; and (**f**) PGNAA sensor gold.

4.2. Impact on Bulk Ore Sorting Potential

Figure 7 presents how the theoretical mass rejection rates and ore upgrading ratios that could be achieved by bulk ore sorting changed spatially due to mixing.

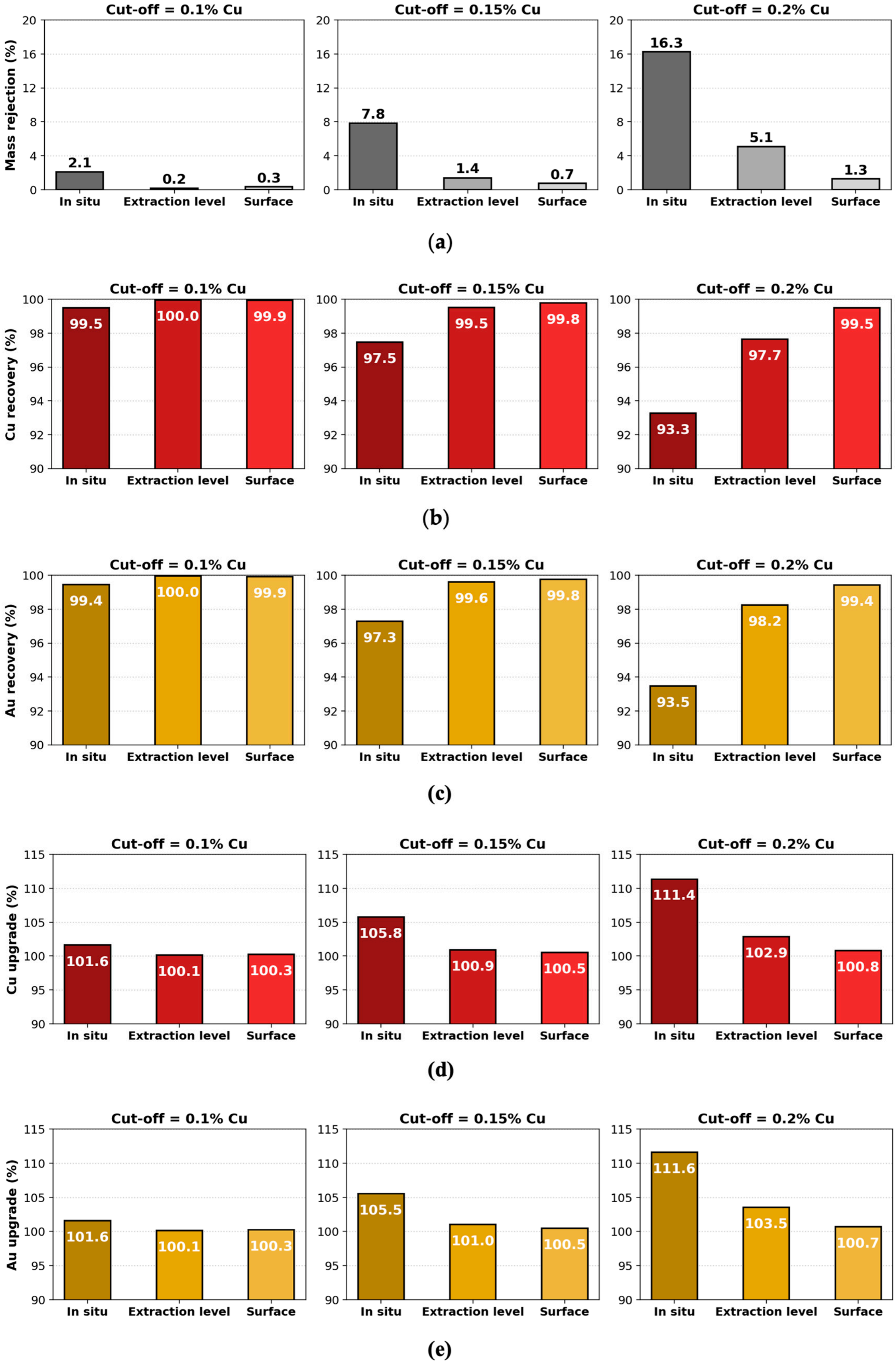


Figure 7. Theoretical recoveries and upgrading ratios of copper and gold and sorter mass rejection rates determined at sorting cut-off grades of 0.1%, 0.15%, and 0.2% Cu at three different locations, represented by the shades of gray, red and gold colours: (**a**) sorter mass rejection; (**b**) copper recovery; (**c**) gold recovery; (**d**) copper upgrading; and (**e**) gold upgrading.

Table 7. The types and parameters of the best-fit probability distribution functions.

Location	Best-Fit Distribution Types and Parameters	
	Cu	Au
In situ (block model)	Burr(shape(c) = 5.85, shape(d) = 0.29, location = 0.06, scale = 0.43)	Lognormal (shape = 0.77, location = −0.06, scale = 0.94)
Extraction level (drawpoint sampling)	Burr (shape(c) = 10.71, shape(d) = 0.27, location = 0.07, scale = 0.37)	Lognormal (shape = 0.79, location = 0.10, scale = 0.71)
Surface (PGNAA sensor)	Student's t (degrees of freedom = 1.83, location = 0.33, scale = 0.02)	Student's t (degrees of freedom = 2.29, location = 1.26, scale = 0.18)

Hypothetically, if mixing had not impacted the variability in grades, 2.1% to 16.3% of the ore caved during the two-month period could have been discarded as waste, depending on the cut-off grade selected for sorting (Figure 7a). Metal recoveries of no less than 93% and upgrading ratios of up to 111% could have been achieved by an on-belt sorting application on the ore blocks if the heterogeneity had not been lost (Figure 7b–e).

The blending of ore during caving and material handling smoothed the ore grades around the mean values, causing a reduction in the low-grade material that a sensor-diverter system could have potentially discarded. The theoretical mass rejection rate declined to 0.3% to 1.3% at the surface (Figure 7a). As the very low upgrading ratios suggest (Figure 7a,d), no opportunity existed to improve the mill feed's quality at any sorting cut-off grade.

Assuming no mixing, one of the active panel caves at Cadia East was determined to be sortable at a sorting cut-off grade of 0.1% in a previous study [25]. Since the mixing, particularly the mixing occurring during the material handling operations, impacts the grade heterogeneity adversely, where the bulk ore sorting potential of that cave may be lost at the surface. However, a sorting opportunity may still exist at the extraction level, as the mixing occurring in the cave columns was determined to be less severe. Sensor technologies mounted on the buckets of production LHDs, for instance, can sense ore grades at drawpoints and exploit the heterogeneity in the caved ore at smaller scales. Provided that the waste material can be handled separately from the ore during the continuous production, bucket-mounted sensors may be used for bulk ore sorting underground.

Alternately, it is suggested that the ability to determine the grades at drawpoints may inform campaigning strategies to limit the loss of heterogeneity and, therefore, take advantage of the sensor systems at the surface [9,17].

5. Conclusions

This study presents how the grade heterogeneity and the bulk ore sorting potential of the Cadia East copper–gold porphyry ore were impacted by the ore mixing occurring during caving and material handling.

The results revealed that the mixing during the handling of the ore underground reduced the grade variability more severely than the mixing within the caves, assuming that the reconciliation between the drawpoint grades and the block model and PGNAA grades was valid. As the ore was blended according to mine planning and subsequently transported from the extraction level to the surface, the grade distributions altered completely, and the grades eventually normalized around the mean values, thereby decreasing the opportunity for sorting. Only insignificant amounts of low-grade material that could have potentially been discarded were reported to the PGNAA sensor.

The results presented in this study offer helpful information for similar cave mining operations exploring the implementation of bulk ore sorting systems. Despite the briefness of the investigation period, the results suggested that an ore sorting opportunity may exist at the extraction level, as the mixing naturally occurring during caving was determined to be less severe.

Provided that the infrastructure required to transport the ore and waste separately to the surface is developed, grade-measuring sensor technologies integrated with LHD equipment can be employed for bulk sorting the ore underground. As an alternative preconcentration strategy, the rapid quantification of grades at drawpoints may inform campaigning to minimize mixing and, hence, take advantage of the on-belt sensor-diverter systems at the surface. In addition, the mobile sensors can be utilized for more rapid and frequent sampling of drawpoints so that an improved production reconciliation can be performed to predict the properties of caved ore more accurately.

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