A new approach to understanding how particle characteristics drive copper recovery at Kansanshi Mine.

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Abstract

Operating flotation plants predictively instead of reactively is challenging given the compositional and microstructural variations of the feed material, especially since chemical assays alone are often insufficient to describe these changes. This challenge is even more pronounced when the target metal is within minerals of unique flotation behavior, e.g. primary and secondary Cu-sulfides together with Cu-oxides, Cu-carbonates, and Cu-bearing silicates. This complex assemblage can be found in the Kansanshi Mine, the case study investigated here that aims to quantify the most important mineralogical properties when forecasting the flotation circuit recovery. The methodology used consists of quantifying the recovery of individual particles with particle-based separation models – information that is used to understand the recovery behavior of each mineral as a function of particle size. This strategy is used on the data of six weeks, to capture variations in feed ore composition. Results shed light on the most meaningful mineralogical properties controlling plant recovery, serving as basis for better troubleshooting daily operations.

1 Introduction

Given the complex mineral assemblage of the Kansanshi deposit, in Zambia, where copper deportment is split between primary and secondary Cu-sulfides together with Cu-oxides, Cu-carbonates, and Cu-bearing silicates, forecasting product grades and recovery is a challenge. The complex copper deportment requires that all mineralogical information should be considered within this task – the baseline for process optimization is at constant change. Operations already collect automated mineralogy information from the feed samples daily, using the TIMA (Tescan Integrated Mineral Analyzer). The onsite mineralogy team at Kansanshi does a weekly mineralogy presentation reviewing the previous week's performance – attempting to convey the key mineralogical information that impacted the performance of the four concentrators, the atmospheric leach, and the high pressure oxidative leach process. While this information is key to better forecast product recovery and grade, it is also a very large dataset – which hinders its daily application using conventional modelling tools. A "particle-categories" report is used for this, attempting to combine key information of mineral speciation, liberation and size in a simplified format. This has been valuable for trouble-shooting and identifying trends and opportunities, however, are the categories used the most meaningful mineralogical variables of the feed? A key objective of this study is to improve understanding of the manner in which these variables impact performance, towards improving the value of the data. In other words, this work aims at identifying the most important mineralogical properties controlling copper grade and recovery in the Kansanshi Deposit, which can then be used for later forecasting production KPIs in daily operations. Particle-based separation models[1] are used for this task. The methodology has provided insight into variables which

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[1]Pereira, L., Frenzel, M., Khodadadzadeh, M., Tolosana-Delgado, R., Gutzmer, J., 2021. A self-adaptive particle-tracking method for minerals processing. Journal of Cleaner Production 279, 123711. https://doi.org/10.1016/j.jclepro.2020.123711

can be potentially grouped and simplified, or groups that may have been oversimplified and could therefore be hiding important trends.

2 Methdology

- Weekly-composite samples of the concentrate and tailings streams from the mixed-concentrator in Kansanshi were collected for six weeks.
- These samples were analysed with TIMA following the protocols established at the site, where every sample is first sized into five classes.
- Data was exported from the TIMA in sqlite format and imported in the simulation platform of the Helmholtz Institute Freiberg for Resource Technology, where each particle is treated individually.
- The following information of each particle is considered:
  - Modal content: the weight of each mineral within a particle.
  - Surface exposure: the area of each mineral on the surface of a particle.
  - Equivalent circle diameter: the size of a particle.
  - Aspect ratio: a measure of elongation of a particle.
- A lasso-regularized logistic regression model is trained with the output samples of each week (concentrate and tailings);
- this model considers the importance of each particle property to its probability of recovery;
- it also eliminates irrelevant or correlated variables to avoid overfitting.
- The metallurgical results (grade and recoveries) observed with the TIMA are then compared to those predicted by the models (cf. Section 3.1).
- Once the prediction errors are confirmed to be low, model results are used to understand the recovery behaviour of individual particles (cf. Section 3.3).

3 Results

3.1 Error estimates

The prediction errors for mineral grades and recoveries are presented in Figs. 1 and 2, respectively. Fig. 3 displays the prediction errors, as Halbich plots, for elements of interest: copper, silica, and sulphur. Altogether, the fact that confidence intervals of predicted and observed results almost always overlap, indicate a good accuracy of the models. The PSMs are able to predict mineral/element grades and recoveries very well. The major prediction errors are observed for chalcopyrite grade in Week 15, with a 10 percentage points absolute error. After discussion with the Kansanshi team, this errors is expected to derive from sampling challenges encountered in this week.

3.2 Copper deportment and phases related to the recovery and loss of the metal

Fig. 4 provides insights about the copper deportment, defined as the modal mineralogy of feed samples weighted by copper grade; the recoverable copper, weighted by both copper grade and the probability of recovery in the concentrate; and the non-recoverable copper, weighted by copper grade and the probability of recovery in the tailings.

To understand Fig. 4, the following equations are necessary. For these equations, discrete particle data is used, such as in the example below, where each particle is described in a row, with values for its weight (w), modal composition $X = (x_1, x_2, ..., x_m)$ considering the m mineral phases of the deposit, and its copper content Cu. Based on the particle-based models, the probabilities of recovery in the concentrate and tailings, respectively R^c & R^t, were calculated for each particle.

w	Mineral 1 (x_1)	Mineral 2 (x_2)	...	Mineral M (x_m)	Cu	R^c	R^t
13	0.2	0.2	...	0.6	0.2	0.6	0.4
11	0.0	0.0	...	1.0	0.3	0.9	0.1

w	Mineral 1 (x_1)	Mineral 2 (x_2)	...	Mineral M (x_m)	Cu	R^c	R^t
...	...	...	...		...	...	...
50	1.0	0.0	...	0.0	0.0	0.1	0.9

First, using this particulate data, modal mineralogy ($\bar{x}$) can be calculated as:

$$\bar{x} = \frac{\sum_i^n w_i \times x_i}{\sum_i^n w_i}$$

where w_i corresponds to the weight of each particle, x is the content of each mineral, and n is the total number of particles.

Building on this concept, one can calculate the deportment of an element, for example Cu, as follows:

$$\bar{x} = \frac{\sum_i^n w_i \times x_i \times Cu_i}{\sum_i^n w_i \times Cu_i}$$

On the same line, this concept can be extended to identify the minerals carrying most of the copper that can be recovered by adding their probability of recovery to the concentrate (R^c) of each particle to the weighted average:

$$\bar{x} = \frac{\sum_i^n w_i \times x_i \times Cu_i \times R_i^c}{\sum_i^n w_i \times Cu_i \times R_i^c}$$

or, on the contrary, using the probability of recovery to the tailings (R^t) of each particle, one can estimate which minerals carry most copper that is being lost to the tailings:

$$\bar{x} = \frac{\sum_i^n w_i \times x_i \times Cu_i \times R_i^t}{\sum_i^n w_i \times Cu_i \times R_i^t}$$

These results are a function of the copper assays assigned to each mineral in the TIMA mineral list and more extensive deportment studies might be required for higher precision. Nevertheless, with these concepts in mind, Fig. 4 illustrates the importance of each mineral in determining copper deportment, recovery to concentrate, and losses. The following trends can be observed:

- The highest shares of copper are hosted by chalcopyrite and chalcocite; nevertheless, significant amounts of copper are also found in other minerals, some of which are recoverable and others not.
- The highest shares of recoverable copper are hosted by chalcopyrite and chalcocite; malachite also accounts for a high share of recoverable copper, especially in Week 18.
- The highest shares of non-recoverable copper are hosted in goethite (particularly in Week 19), others in Cu-bearing micas, other silicates, malachite (especially in Week 8), and biotite (in Week 19).
- Some of the copper found in chalcopyrite ends up in the tailings. Noticeably, most losses related to chalcopyrite recovery issues happened in Week 11.

3.3 Recovery trends of liberated particles

The recovery trends of liberated particles are discussed next. The focus on liberated particles first is to assure an analysis of the recovery behaviour of each of these minerals individually, without the influence of associated phases. These are displayed as a function of particle size for the most relevant minerals in terms of copper deportment, recoverable copper, and non-recoverable copper, namely: chalcopyrite, chalcocite, malachite, cuprite, quartz, biotite, goethite, pyrite, albite, calcite, muscovite, other Cu-bearing micas, other silicates, and other oxides.

In Fig. 5, we can observe the following trends for chalcopyrite:

- The recovery of liberated chalcopyrite particles is generally high, mostly above 80%.
- The recovery of this target mineral is the lowest in weeks 15 and 18, especially regarding particles finer than 20 µm.

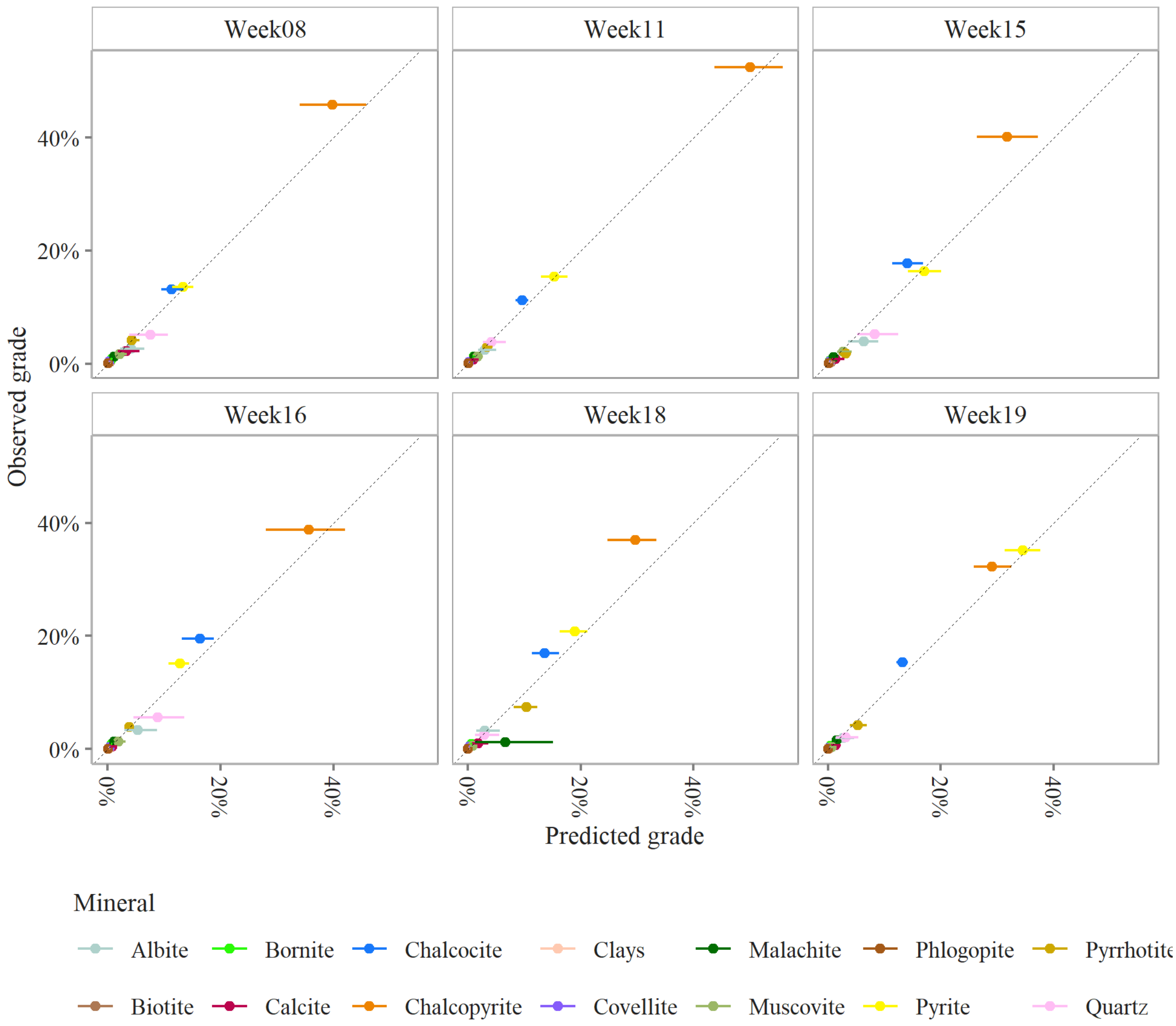

Figure 1: Comparison between predicted and observed grade for each week.

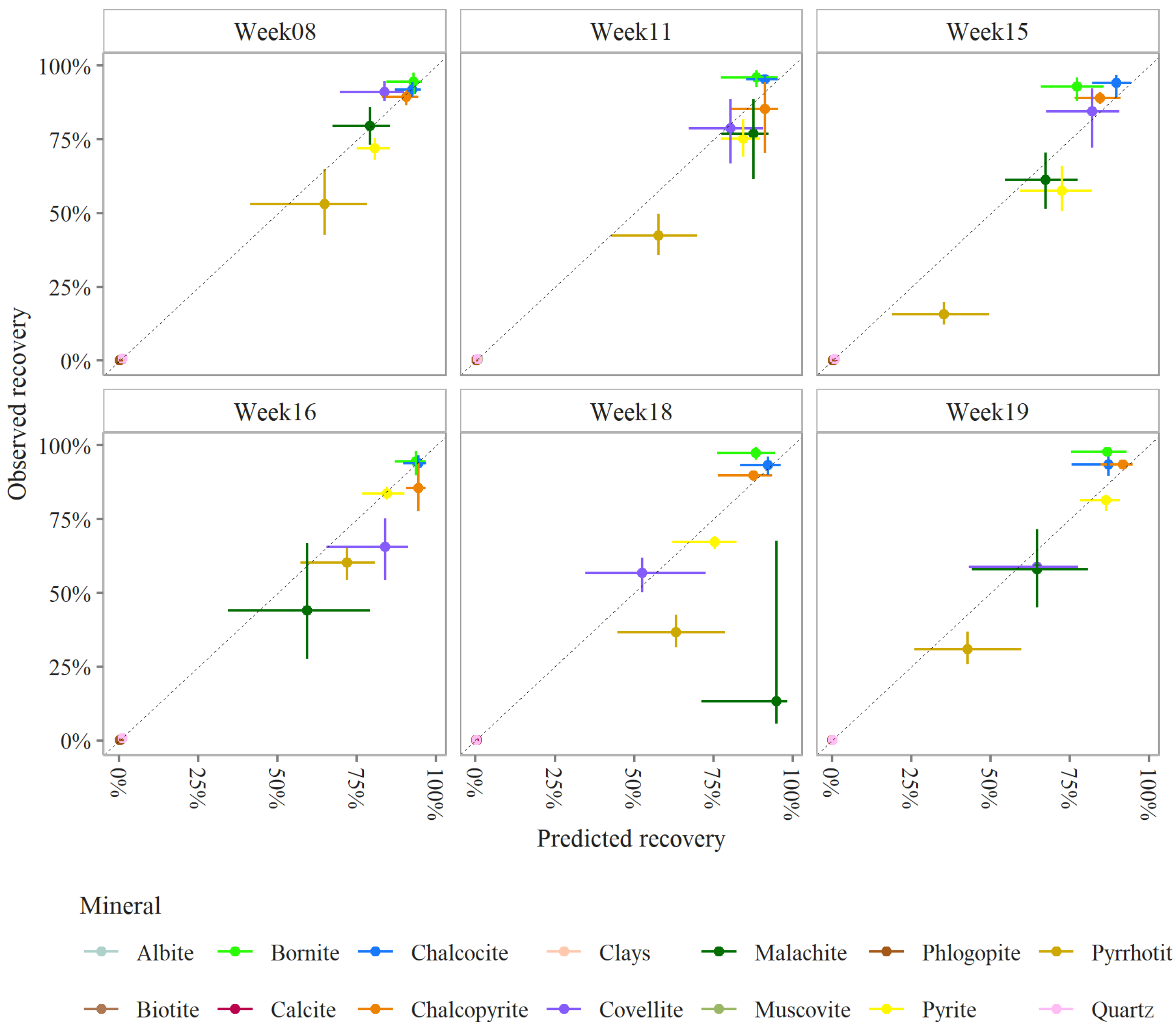

Figure 2: Comparison between predicted and observed recovery for each week

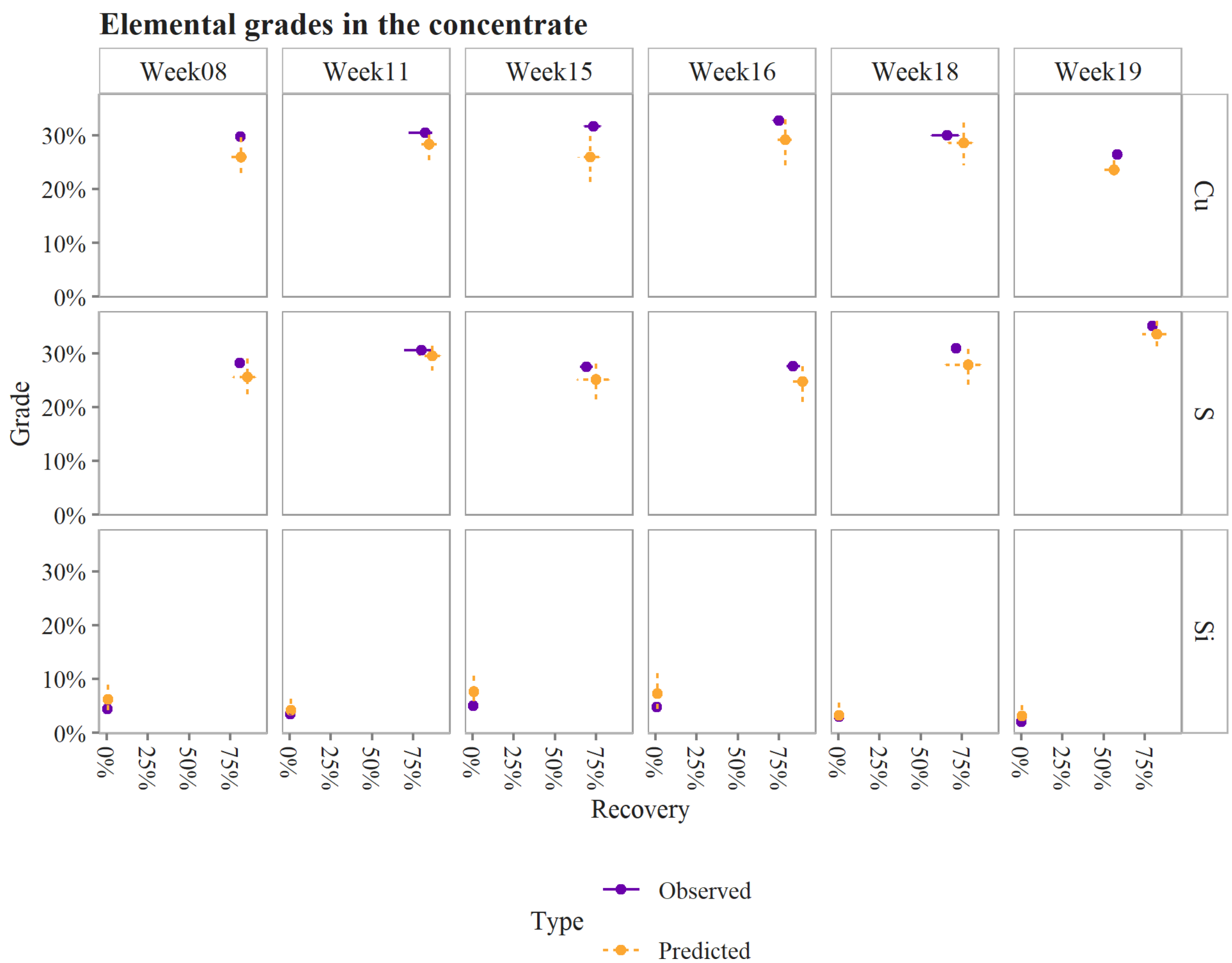

Figure 3: Comparison between predicted and observed enrichment factor vs. recovery trends under different operating conditions

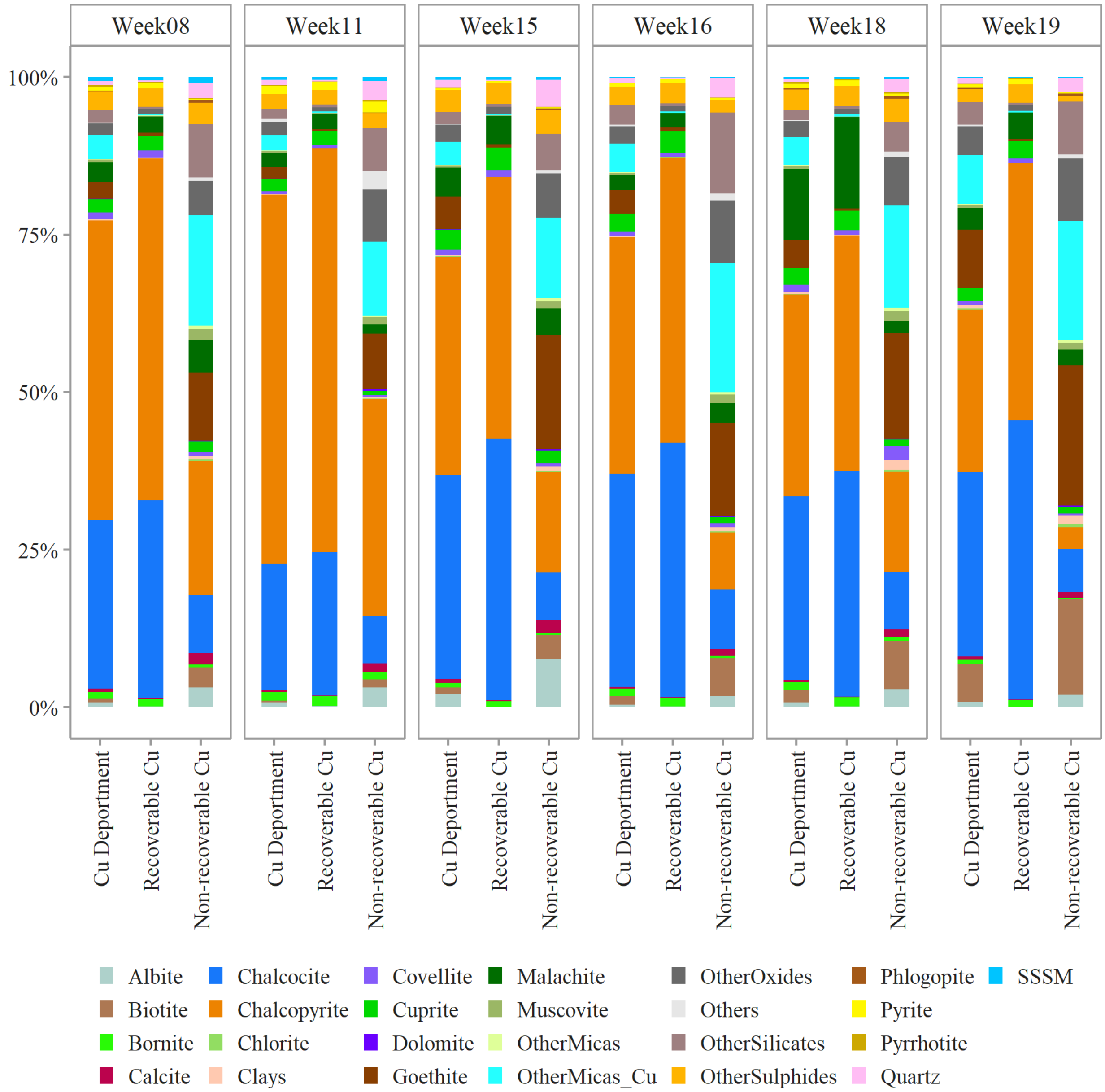

Figure 4: The modal mineralogy of feed samples weighted by the copper grade (copper deportment), the copper grade and the probability of recovery in the concentrate (recoverable copper), and the the copper grade and the probability of recovery in the tailings (non-recoverable copper)

- In the case of week 11, particle size seems to influence the recovery of chalcopyrite particles less than it does in the other weeks;
- for all other weeks, the recovery of particles below 20 µm is slightly lower;
- yet, no drop in recovery is observed for coarser particles.
- Some slightly overlapping trends are observed within the results of a week. This can be attributed to the different ccp species grouped under "Chalcopyrite", which have slightly different recovery behaviours.
- Interestingly, the other ccp phases, namely "Chalcopyrite_mixed spec", "Chalcopyrite_surfdef", "Chalcopyrite_lowS", and "Chalcopyrite_CC", generally occur at finer particle sizes and show lower recoveries compared to standard chalcopyrite.
- A different trend is seen for Chalcopyrite_lowS in weeks 11 and 18, where its recovery exceeds that of standard chalcopyrite, regardless of particle size.

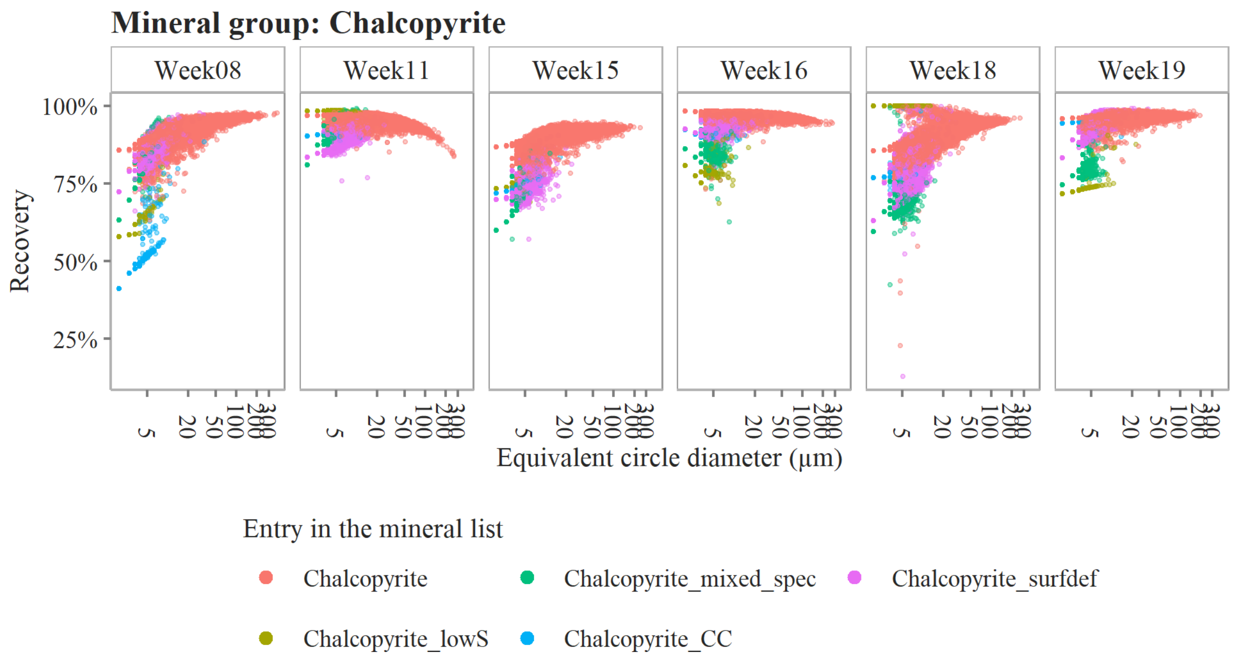

Figure 5: Chalcopyrite - probability of recovery of liberated particles.

In Fig. 6, we can observe the following trends for chalcocite:

- The recovery of liberated chalcocite particles is generally high, mostly above 90%.
- The recovery of this target mineral is slightly lower in Week 19.
- The influence of particle size on the recovery of chalcocite is generally low across all weeks.
- Some slightly overlapping trends are observed within the results of a week. This can be attributed to the different species grouped under "Chalcocite";
- among these, "Chalcocite_low_counts" consistently shows lower recovery than standard chalcocite, whereas "Chalcocite_goethite_27Cu", "Chalcocite_goethite_48Cu", and "Chalcocite_Fe" locally show higher recoveries than standard chalcocite.

In Fig. 7, we can observe the following trends for malachite:

- The recovery of liberated malachite particles is moderate to high, varying between 50 and 100%.
- This explains why the content of recoverable and non-recoverable malachite in Fig. 4 often seems to be comparable.
- The two phases grouped under "Malachite", namely standard malachite and "Malachite_mixed spectra", show similar or overlapping trends in weeks 8, 15, and 16, and markedly different trends in weeks 11, 18, and 19. The latter weeks are also those characterized by higher prediction errors for Malachite (Fig. 2).
- Generally, standard malachite shows higher recovery than Malachite_mixed spectra.

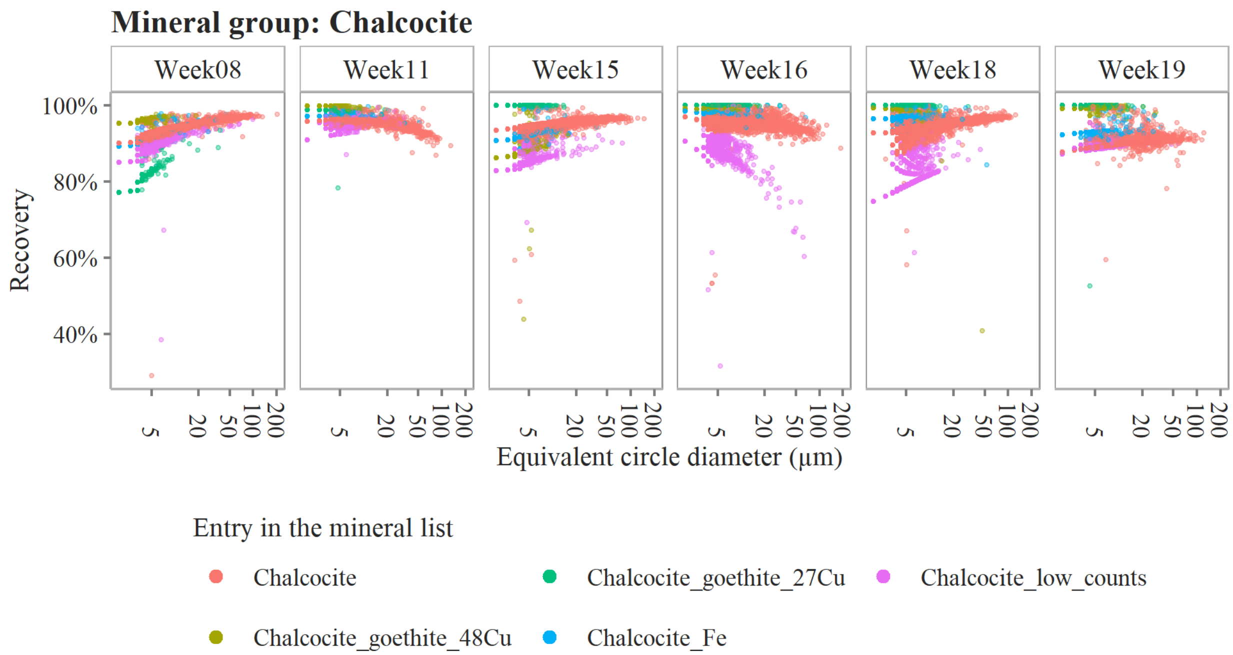

Figure 6: Chalcocite - probability of recovery of liberated particles.

- In the case of Week 16, particle size seems to influence the recovery of malachite particles less than it does in the other weeks;
- for all other weeks, the recovery of particles below 5 µm is generally lower, but opposite trends are also observed (e.g., in Week 19 for Malachite_mixed spectra).

In Fig. 8, we can observe the following trends for quartz:

- The recovery of liberated quartz particles is very low, mostly below 5%.
- for all other weeks, the recovery of particles above 30 µm is slightly lower.

In Fig. 9, we can observe the following trends for biotite:

- The recovery of liberated biotite particles is very low, mostly below 5%.
- The recovery of Cu-bearing biotite is high in week 11.
- The influence of particle size on recovery is more significant for other mineral phases grouped under “Biotite” than for standard biotite, as particles of these minerals, when finer than 10 µm, show higher recoveries.

In Fig. 10, we can observe the following trends for pyrite:

- The recovery of liberated pyrite particles is moderate to high, mostly between 50% and 100%.
- The recovery of this gangue mineral is the lowest in weeks 11 and 15.
- The influence of particle size on the recovery of pyrite is generally high across all weeks, as particles larger than 30 µm show the highest recovery.
- Some slightly overlapping trends are observed within the results of a week. This can be attributed to the different species grouped under “Pyrite”.
- Interestingly, most of the phase “Pyrite_6Cu” is recovered, whereas “Pyrite_mixed spectra” shows typically lower recovery than standard pyrite.

In Fig. 11, we can observe the following trends for albite:

- Two main trends can be observed in the recovery results for albite across all weeks. This is because the mineral group “Albite” includes both standard albite and “Albite_1.7Cu”, which have different recovery behaviors.

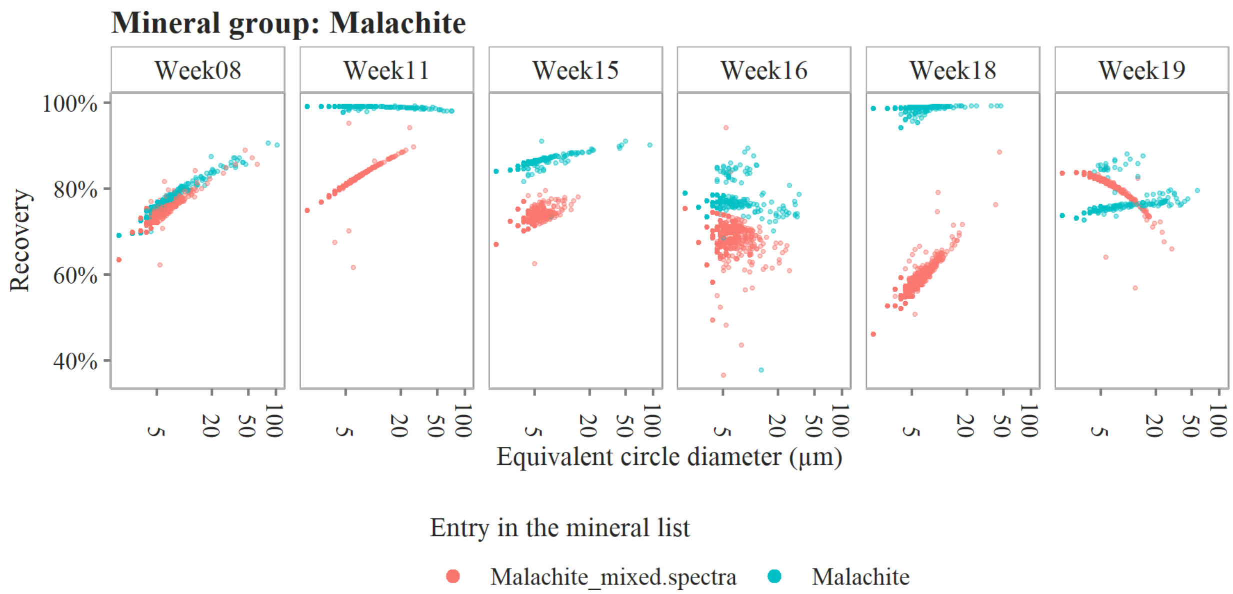

Figure 7: Malachite - probability of recovery of liberated particles.

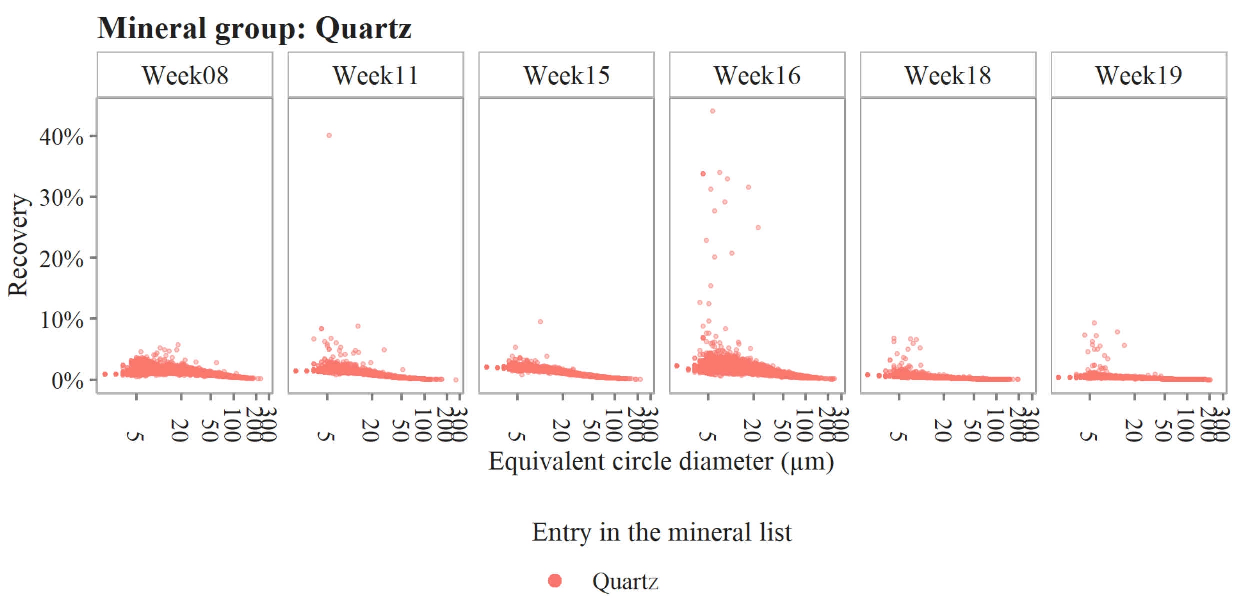

Figure 8: Quartz - probability of recovery of liberated particles.

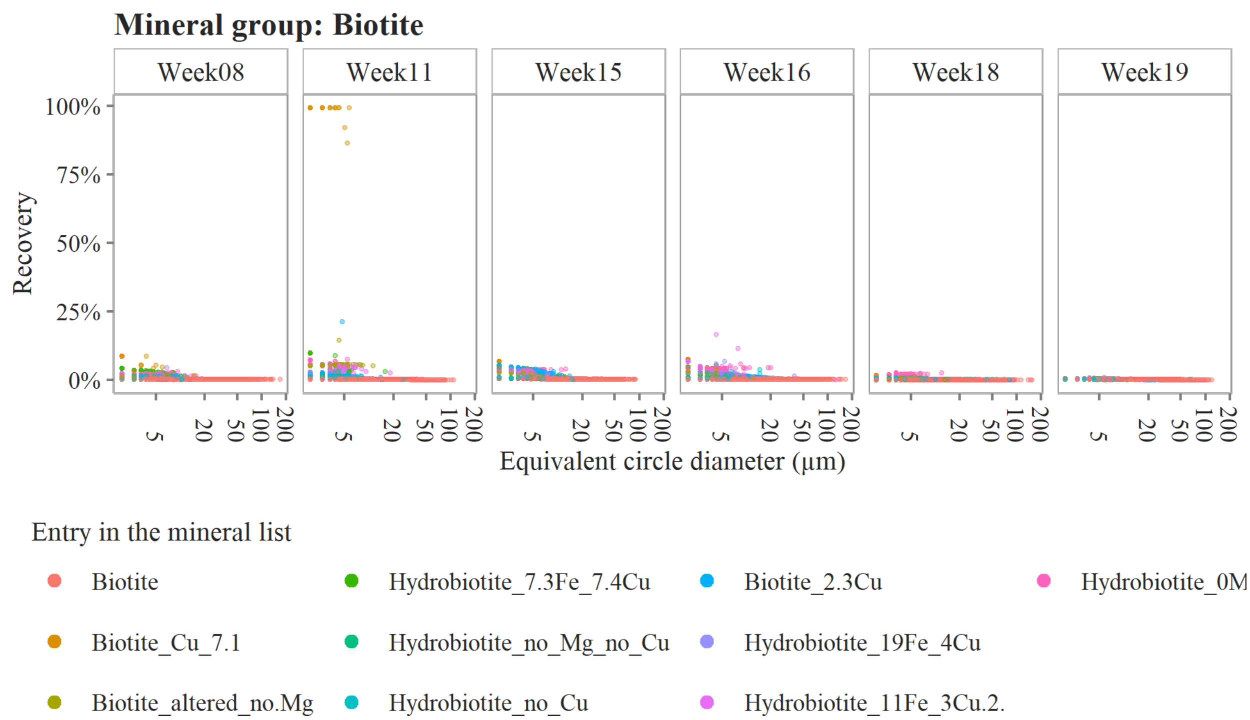

Figure 9: Biotite - probability of recovery of liberated particles.

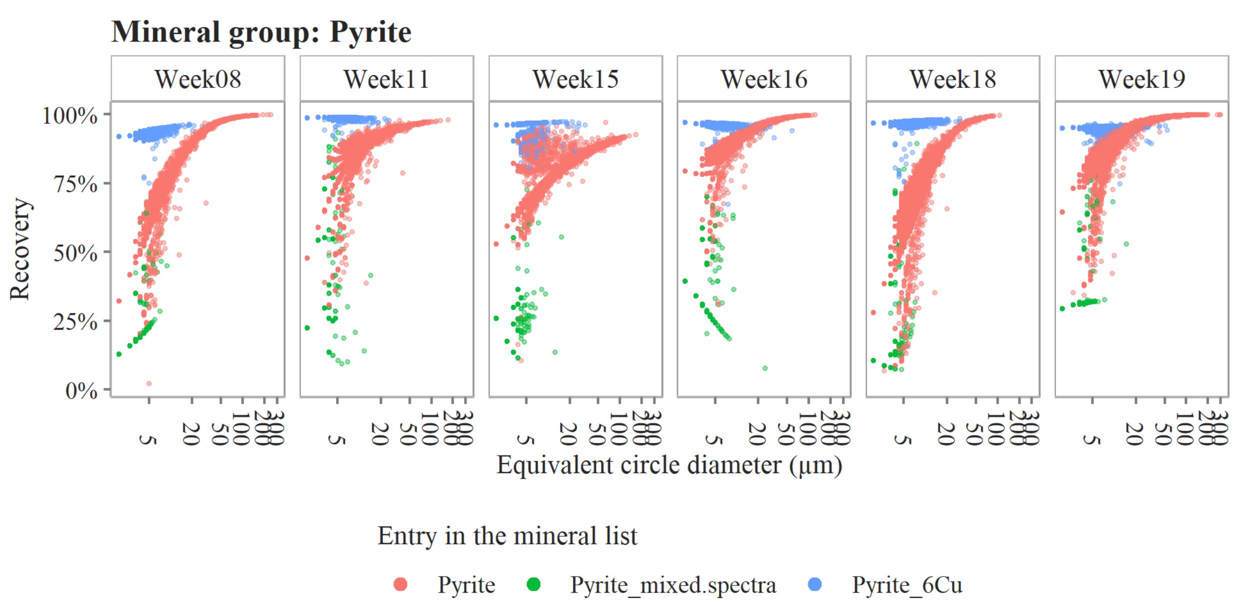

Figure 10: Pyrite - probability of recovery of liberated particles.

- The recovery of liberated standard albite particles is very low (close to 0%) and shows no correlation with particle size.
- For Albite_1.7Cu, the recovery of liberated albite particles is generally low, mostly below 20%. Across all weeks, particles larger than 3 µm show an increase in recovery.
- For Albite_1.7Cu, the recovery is the highest in Week 16.

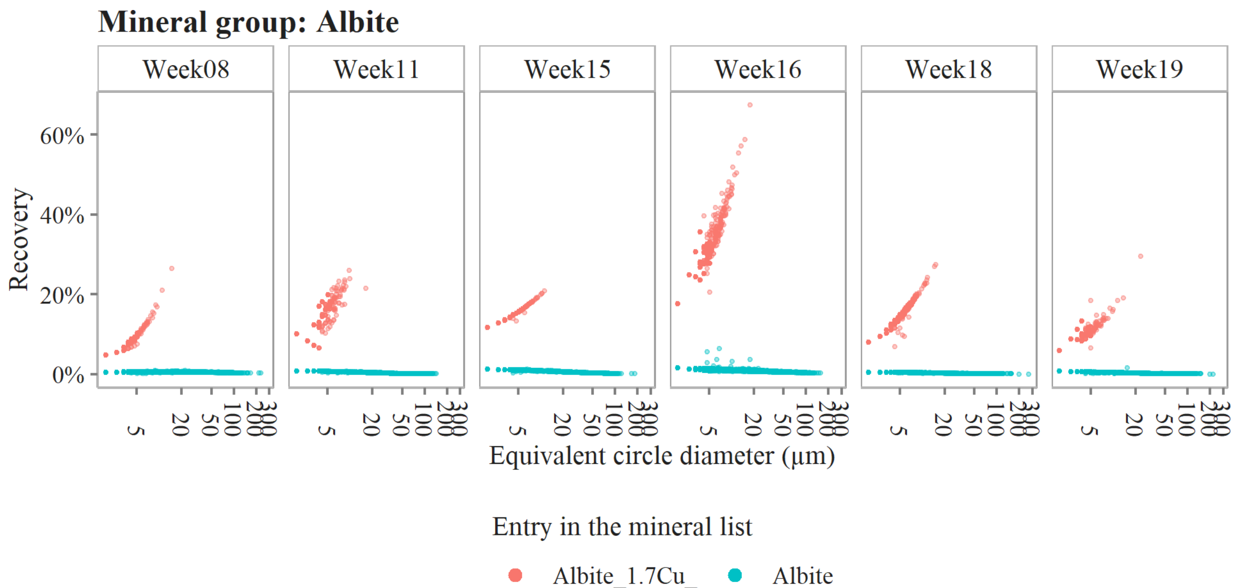

Figure 11: Albite - probability of recovery of liberated particles.

In Fig. 12, we can observe the following trends for calcite:

- Two main trends can be observed in the recovery results for calcite across all weeks, mostly because of the markedly different recovery behaviours shown by standard calcite and “Calcite_chalcocite_mixed spectra” and “Calcite_goethite_Cu”.
- For standard calcite, the recovery of liberated particles is very low (close to 0%) and shows no correlation with particle size.
- For Calcite_chalcocite_mixed spectra, the recovery of liberated particles is generally low, mostly below 40%.
- The recovery of Calcite_chalcocite_mixed spectra is higher above 3 µm across all weeks, and is the highest in Week 8.
- Some slightly overlapping trends (e.g., dense cloud of points in Week 16) are observed within the results for each week. This is due to the presence of more than two minerals grouped under “Calcite”.

In Fig. 13, we can observe the following trends for muscovite:

- Two main trends and can be observed in the recovery results for muscovite across all weeks, mostly because of the markedly different recovery behaviours shown by standard muscovite and “Muscovite_2.9Cu”.
- For standard muscovite, the recovery of liberated particles is very low (close to 0%) and shows no correlation with particle size.
- For Muscovite_2.9Cu, the recovery of liberated particles is generally low, mostly between 10 and 50%.
- The recovery of Muscovite_2.9Cu is higher above 3 µm across all weeks, and is the lowest in weeks 18 and 19.
- Some slightly overlapping trends are observed within the results for each week. This is due to the presence of more than two minerals grouped under “Muscovite”.

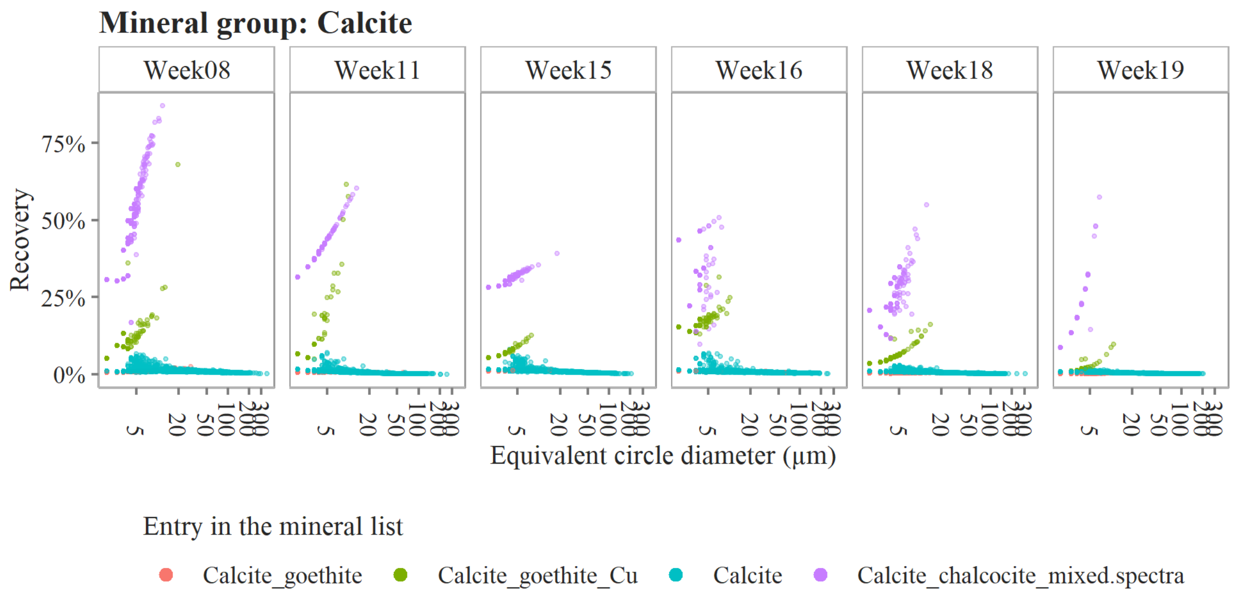

Figure 12: Calcite - probability of recovery of liberated particles.

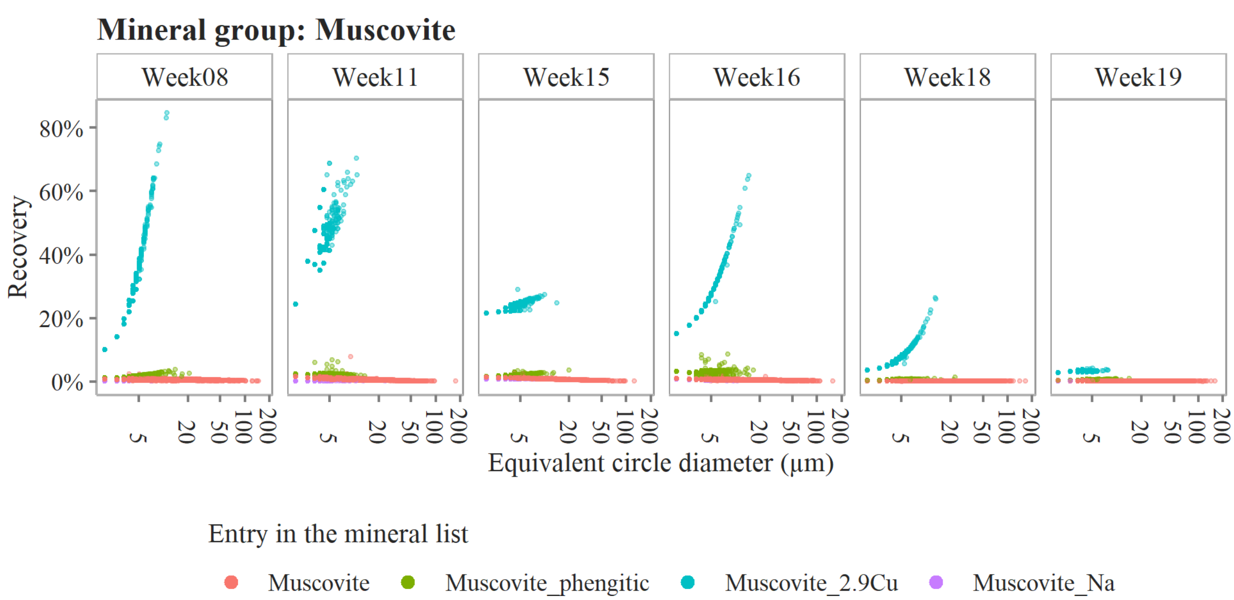

Figure 13: Muscovite - probability of recovery of liberated particles.

3.4 Recovery as a function of liberation

In Figure 14, the recovery trends as a function of particle size and liberation are shown for ore minerals. As expected, ore minerals, specially chalcopyrite, have a much lower recovery when non-liberated (Fig. 14). To explore the effect of association in the recovery of chalcopyrite-bearing particles, a closer look is taken to Week 18, where the recovery of this target mineral is impaired the most by liberation issues (Fig. 14). Fig. 15 displays the recovery behaviour of chalcopyrite-bearing particles according to the weight-dominant mineral in each particle. The recovery trends in this case are very similar to the recovery trends observed for liberated particles of these minerals in Section 3.3.

3.5 Attempt of training one predictive-model to be used in daily operations

The long-term perspective of having one model to be used in daily operations is the major goal. While this study focused on how to simplify particle datasets according to the most important mineralogical properties controlling copper recovery, an alternative approach is also explored – to train a single particle-based separation model applicable for daily operations. Ideally, this model should be able to forecast the copper grade and recovery of the final concentrate. For that, the recoverability of the many copper-bearing minerals must be predicted, also considering the type of particles they are encountered in. Thus, in this exploratory exercise, we evaluate the accuracy of using a single particle-based separation model to forecast the grade and recovery of different minerals for all the Weekly-data available for the study. For that, we trained one PSM using all particle data collected for the study. The accuracy of this model is compared to the model trained with the particle data available for the said week itself. Theoretically, this model should yield the most accurate predictions.

Results of these strategies are presented as Halbich Plots for copper, silica, and sulphur in Fig. 16 . In general, the accuracy of using a single PSM is comparable to the PSM trained with the samples of the week itself. These results demonstrate the potential of using a global PSM in daily operations to predict the recovery of every new incoming feed.

4 Discussion and conclusion

- This study thoroughly analyses the recovery trends of many mineral phases from the Kansanshi deposit, shedding light to the influence of particle size, liberation, and association to their recovery.
  - While the influence of particle shape on recovery has been investigated, a clear trend was not identified and thus it has been left out of this study.
- Importantly, the minerals mostly responsible for copper losses could be identified:
  - Chalcopyrite and chalcocite are the main source of copper in the deposit, and the processing behaviour of these minerals did not change much across the different weeks.
- Pyrite is the main gangue mineral that typically gets recovered into the concentrate:
  - coarser pyrite particles are recovered more than the fine ones, indicating the possible recovery via true flotation of this sulfide.
- Many non-sulphide gangue minerals end up in the concentrate when some copper-bearing phases are found on their surface, as reported in Section 3.3:
  - this indicates that mineral surfaces are activated already with tiny amounts of copper, which is in-line with the observed high recovery of pyrite.
- No clear trends could be observed with the operating conditions available for this study – thus its analysis has been left out of this study.
- According to the results presented in Section 3.5, it seems possible to train a single particle-based separation model to be used in daily operations, capable of forecasting the processing outcome of new incoming feed samples.

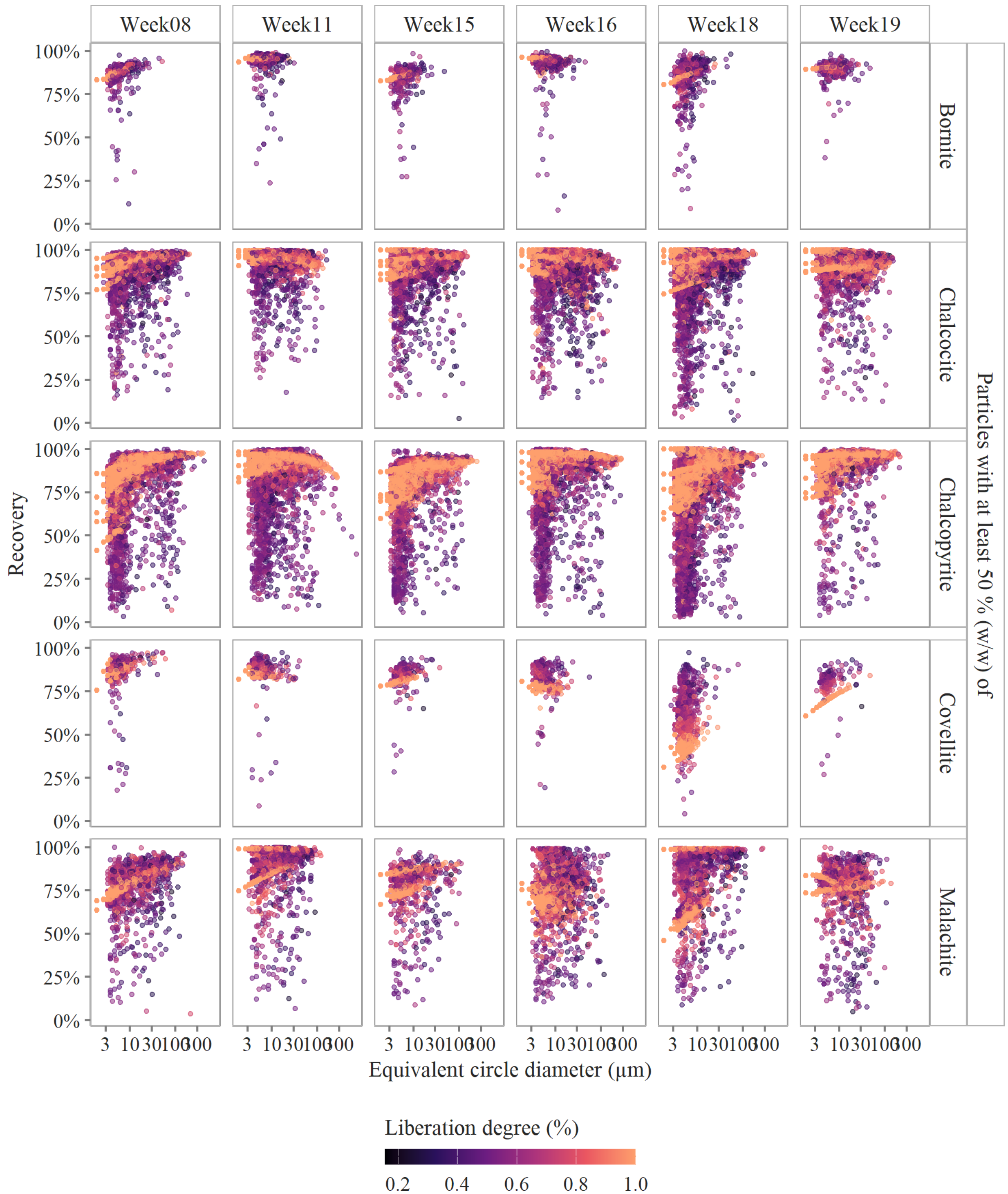

Figure 14: Probability of recovery of particles containing each of the ore minerals according to their liberation degree.

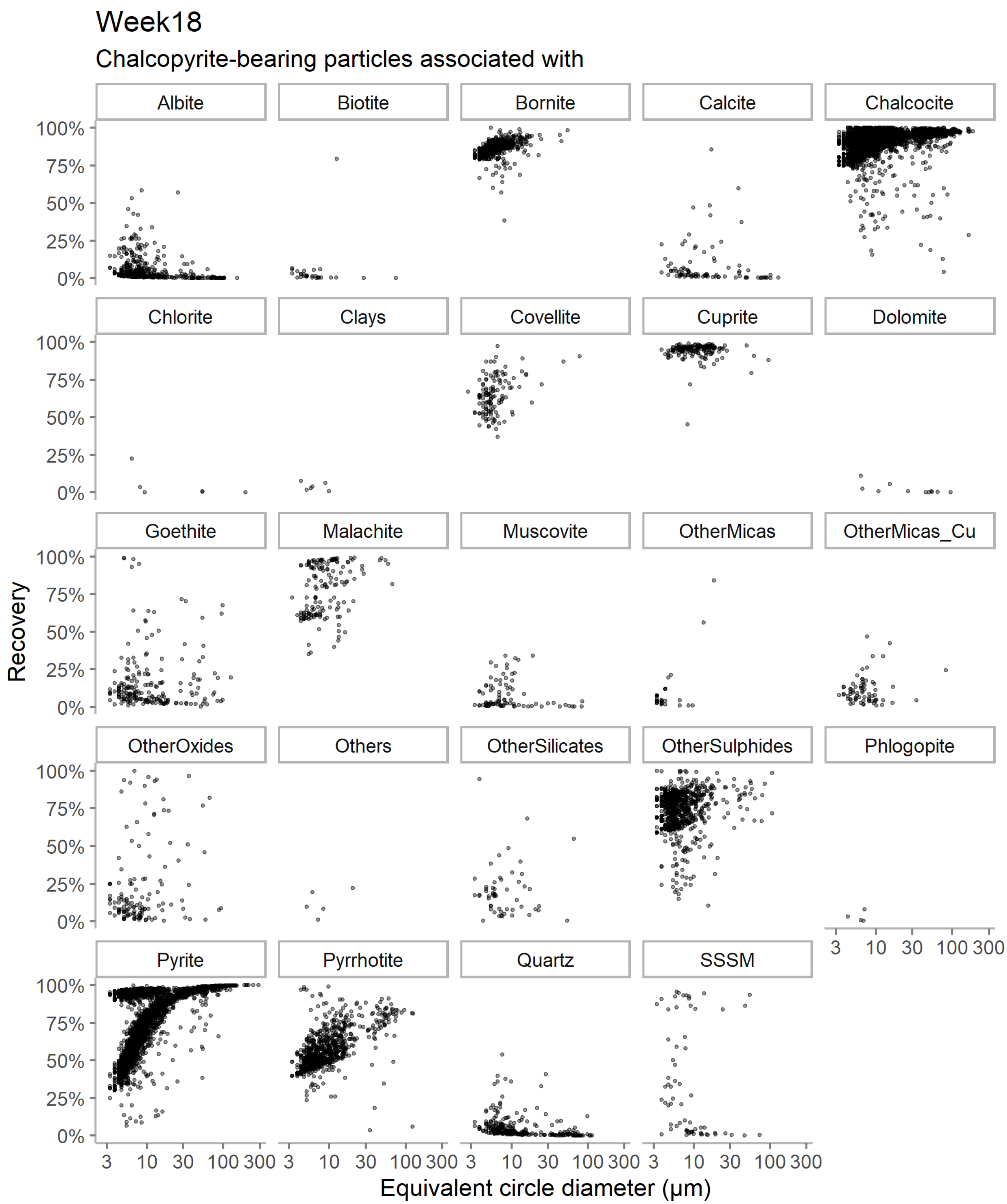

Figure 15: Probability of recovery of particles containing chalcopyrite according to their size, liberation, and association.

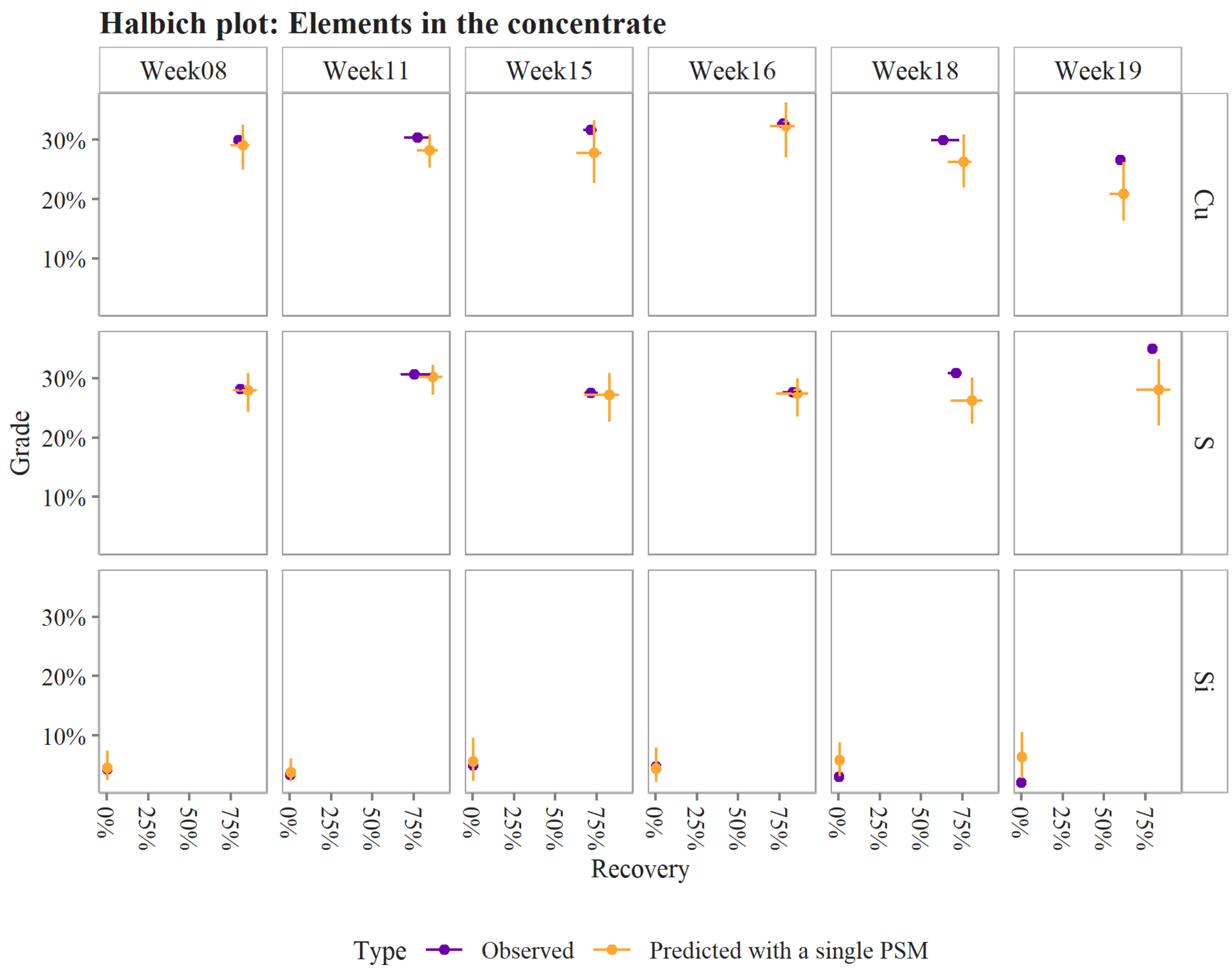

Figure 16: Comparison between predicted and observed enrichment factor vs. recovery trends under different operating conditions