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Experimental investigation into the kinetics of Falcon UF concentration: Implications for fluid dynamic-based modelling

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Abstract

Centrifugal gravity separators, such as the Falcon UltraFine (UF) concentrator, are the most common gravity concentration techniques used for fine particles processing. Hence, understanding the kinetics and separation mechanisms at play within these separators is of paramount interest. Recent research yielded a predictive physical model for the Falcon UF which however does not explain some results obtained with industrial ores. The Falcon UF kinetics have been investigated through the processing of fine-grained ores from the Altenberg tin deposit (Germany), the Tabuaço tungsten deposit (Portugal), a synthetic iron ore as well as results from previous studies on kaolin residues. Results have shown an evolution of Falcon UF performance with time/feed mass in contradiction with the stationary separation hypothesis on which the physical model was based. In terms of Falcon UF separation timing, four phases can be distinguished. First, upon initial feeding of the bowl, particles are trapped or rejected depending on their settling velocity. It yields a relatively ineffective selection according to density so that only ultrafine particles are ejected from the bowl, resulting in the quick growth of the concentrate bed. When the bed reaches a critical size, recovery and enrichment continue to increase through selective resuspension phenomenon that favours the concentration of dense particles and the ejection of larger particles. This way, the bed builds up while the content of concentrate bed surface evolves until resuspension balances the stream of dense material reaching the bed and recovery drops. The evolution of partition curves over time confirmed the low recovery of ultrafine particles during the whole operation but also showed a decrease of coarse particles recovery with time. It suggests that the second separation mechanism is less sensible to particle size compared to the first one and that size even has a negative impact on recovery. Furthermore, erosion figures in furrows are observed in the concentrate bed which may play locally an active role in the separation. These observations suggest that two separation mechanisms are at play. Firstly, differential particles settling within the flowing film which is already accounted for in the existing physical model. Secondly, resuspension of particles from the concentrate bed by the action of a lift force acting preferentially on coarse particles deposited at the surface of the bed and resulting in the rejection of coarser and lower-density particles. The addition of a lift force component to the existing model is discussed and a resuspension criterion is proposed as a guidance of the physics involved in this second separation mechanism. Future developments will require a dynamic model which would need to integrate the evolution of the concentrate bed content over time.

Key words: Gravity concentration, Centrifugal separation, Falcon concentrator, modelling, fine particle separation

1. INTRODUCTION

Enhanced gravity separators, which use additional centrifugal force to enhance the separation, are the most common gravity concentration techniques used for fine particles processing. Centrifugal separators can be seen as a ramification of the flowing film gravity concentrators category which employs centrifugal force to enhance the relative settling velocities of particles components [1]. These separators are mainly represented by the Knelson and Falcon concentrators as well as the Kelsey Jig and Multi Gravity Separator (MGS). The two latter devices actually use one additional separation mechanism, *i.e.* stratification for the Kelsey jig and shaking for the MGS. Falcon concentrators consist in a conical bowl capable of spinning at high rotation speed (up to 600 G), enabling the separation of fine particles based on their density [2]. The slurry is fed at the bottom-centre of the bowl and flows upwards along the bowl wall due to combined effect of bowl opening angle and centrifugal force. A retention zone delimited just before the bowl outlet retains the dense particles inside the bowl while the light particles are flushed over the top of the separator with the process water [3]. Three Falcon types are available industrially, namely, Falcon SB (Semi-Batch), Falcon C (Continuous), and Falcon UF (UltraFine), which differ by the way particles are trapped in the retention zone. Falcon SB series use fluidised annular grooves upstream of the bowl outlet to avoid compaction and adjust the retention capacity by injection of counter pressure water through the concentrate ridges. Falcon C series are operated on a continuous basis without any water addition due to subdivisions into hoppers with air operated valves to control the flow in the retention zone. Falcon UF concentrator series use a smooth bowl with a retention zone delimited by a slight reduction in diameter at the outlet, specifically designed to recover ultrafine particles ($-5\ \mu\text{m}$). The bowl can be equipped with a variable lip in the retention zone to adjust its capacity [4]. No fluidisation counter-pressure is applied in these concentrators to prevent flushing out fine particles. Both Falcon SB and UF are operated in semi-batch mode and must be stopped before saturation of the bowl to avoid concentrate losses by erosion or by unselective separation [5,6]. Thanks to its design oriented towards ultrafine particles recovery, Falcon UF has been successfully employed to recover both metal-bearing heavy minerals (tin, tungsten, tantalum, chrome, and cobalt) and native metals (gold, silver) with particle sizes down to $3\ \mu\text{m}$ [4]. Such performance however is material/ore-dependent and may vary from one mining operation to the

70 other. Hence, the development of a robust predictive model for Falcon UF separation performance
 71 considering both material properties and operating conditions would allow to optimise its overall
 72 performance, to control the quality of the concentration product or simply to assess the amenability of
 73 Falcon UF for a given application without the need for extensive trials.

74 Recently, fundamental modelling studies through numerical simulation methods such as Discrete
 75 Element Methods (DEM) or Computational Fluid Dynamics (CFD) have looked into the separation
 76 mechanisms as well as the influence of feed properties and operating parameters for Knelson
 77 concentrators [7–10]. The separation process within Knelson and Falcon concentrators bowls relies on
 78 two main mechanisms, differential settling of particles in the flowing film along the inside wall of the
 79 bowl [5,11–14] and selective reorganisation of the particles in the retention zone through fluidisation
 80 [15,16], the latter being the predominant mechanism in Knelson concentrators [17]. However, since
 81 Falcon UF is not fluidised, this second separation mechanism is unlikely to occur in the smooth UF
 82 bowls as illustrated by the presence of a layer of denser material at the surface of the concentrate bed
 83 through the entire height of the bowl [18]. Hence, it is believed that there should be no reorganisation
 84 of particles in the concentrate bed, which leads to the model assumption that all the particles entrapped
 85 before saturation belong to the concentrate [19]. Based on a mechanistic understanding of the
 86 separation physics within those bowls, Kroll-Rabotin et al. [19–21] derived a physical model of the
 87 Falcon UF concentrator for diluted suspensions by solving a simplified particle transport equation
 88 analytically:

$$C_p = \max\left(0, \min\left(\frac{4\pi}{9}\lambda_0 Q^{-1} \omega^2 (\rho_p - \rho_f) d_p^2 \rho_f^{-1} \nu^{-1} R_{min} R_{max} H_{bowl} I\right)\right) \quad (1)$$

89 in which C_p is the recovery to the concentrate, Q , and ω are the operating parameters (volume flow
 90 rate, and rotation rate), d_p and ρ_p are the particles properties (size and density), ρ_f and ν are the fluid
 91 density and kinematic viscosity, R_{min} , R_{max} and H_{bowl} are the dimensions of the bowl and λ_0 is a
 92 calibration constant. A full description of the forces acting on a particle within the Falcon UF bowl, as
 93 well as a detailed derivation of the model can be found in Refs. [19,20]. This model, which has been
 94 validated in laboratory conditions using pure-silica samples [22], relies on a number of assumptions,
 95 including the existence of a stationary separation stage before saturation and the no-resuspension of

96 trapped particles in the bowl retention zone [19,20]. However, the model does not explain the increase
97 in separation performance with time/feed mass before the bowl saturation as well as the potential
98 evidences of resuspension as observed by some authors with industrial ores [6,11,12], who suggested
99 that bed erosion phenomena may affect the efficiency of the separation over time.

100 This experimental study aims at identifying the mechanisms involved in Falcon UF centrifugal
101 concentration with the objective of confirming or rejecting the hypotheses on which the current
102 physical model is based, therefore defining its limitations and suggesting potential points of
103 improvement. The third section presents experimental works used to question the stationarity of the
104 separation and the no-resuspension hypothesis. Based on the conclusions drawn from these
105 experiments, the fourth section presents a physical analysis of the separation under the new
106 hypotheses, which leads to the integration of a resuspension component to the fluid dynamic-based
107 model.

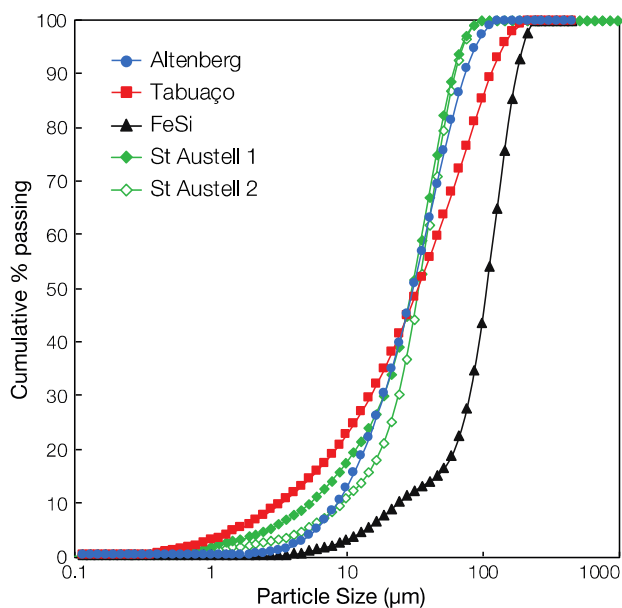
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109

2. MATERIALS AND METHODS

110 2.1. Materials

111 The composite samples used in this study are considered to represent typical low-grade and fine-
112 grained complex ores. They consist in a greisen-type tin (Sn) ore (Altenberg, Germany), a tungsten-
113 bearing skarn ore (Tabuaço, Portugal) and a synthetic iron ore composed of a binary mixture of quartz
114 and ferrosilicon (FeSi). All samples have been crushed using a laboratory jaw crusher and ground
115 using a laboratory ball mill to reach suitable particle size for the tests (Figure 1). The Altenberg
116 sample is a blend of 3 distinct facies with a mineralogy dominated by quartz, micas (zinnwaldite,
117 biotite), feldspars and topaz with cassiterite (SnO_2) as the main Sn-bearing mineral, mostly distributed
118 (47 wt.%) in the -25+10 μm fraction with a grade of 1.9% Sn (Figure 2a). The Tabuaço sample is
119 mainly constituted of dense calcium-bearing silicates (vesuvianite, zoisite, grossular), fluorite, apatite
120 and light silicates, mostly feldspars. Scheelite (CaWO_4) is the main host mineral, mostly distributed
121 (50 wt.%) in the fine size fractions (-63 μm) with an average grade of 1.0% WO_3 (Figure 2b). The
122 synthetic iron ore was obtained by mixing 50-200 μm pure quartz with -50 μm ferrosilicon (FeSi) with
123 a 2:1 ratio.

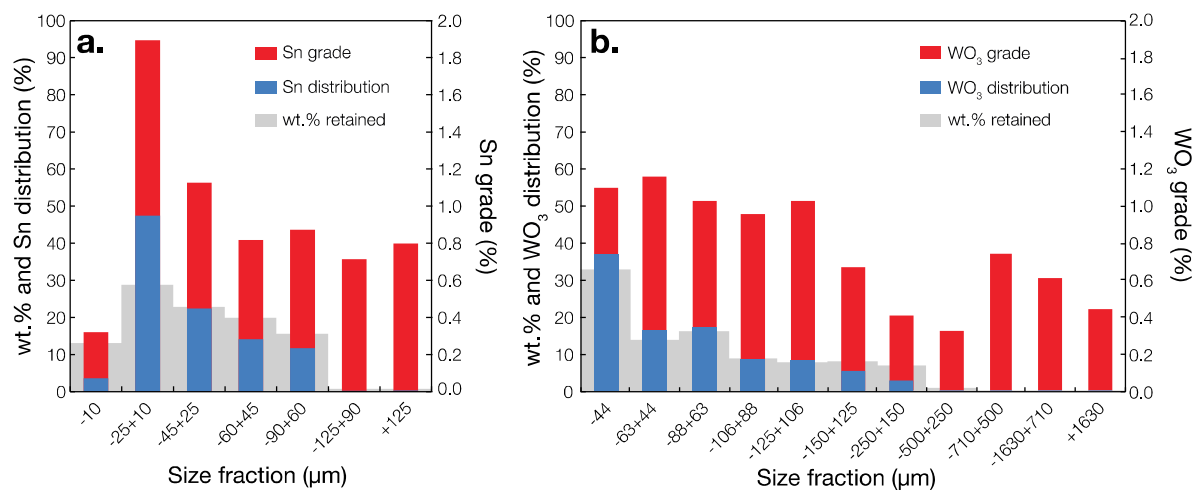


124

125

Figure 1. Particle size distribution of the composite samples.

126



127

Figure 2. Grade and distribution by size-fraction in the Altenberg (a) and Tabuaço (b) composite samples.

129

130 2.2. Chemical analyses

131 Altenberg and Tabuaço samples were dried in an oven at 80°C, weighted and ground in a
 132 laboratory ring mill to obtain a -10 μm powder which was then riffled in representative aliquots.
 133 Chemical analyses were carried out by Energy Dispersive X-Ray Fluorescence spectroscopy (ED-
 134 XRF) using a Niton™ XL3t (Thermo Scientific) portable XRF analyser. External calibration of the
 135 XRF has been completed using duplicate analyses from Inductively Coupled Plasma Mass

136 Spectrometry (ICP-MS, Thermo Elemental X7) for the trace elements analyses performed at the
137 *Service d'Analyses des Roches et des Minéraux* (SARM-CNRS, Nancy, France). Alternatively, the
138 FeSi content of the iron synthetic ore was assessed by recovering the ferrosilicon particles from the
139 test samples using magnetic separation and by weighting the magnetic and non-magnetic fractions
140 with a precision scale.

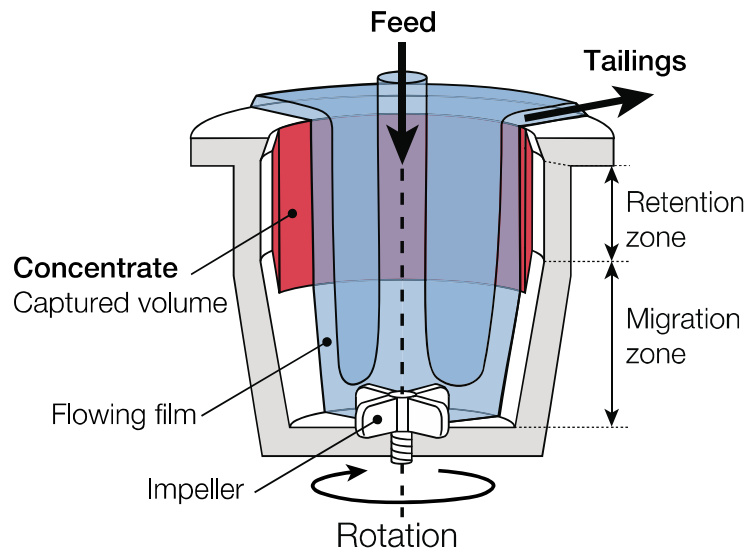
141 **2.3. Particle size analysis**

142 Particle size analyses were performed following two distinct techniques depending on the use of
143 the size fraction. When the contents of each size fraction had to be separated for further analyses,
144 particle size analysis was performed using a Rotap apparatus and a standard laboratory wet and dry
145 sieving procedure (ISO 2591-1:1988). Alternatively, more detailed particle size analyses were
146 obtained by laser light scattering using a Helium-Neon Laser Optical System Mastersizer 3000
147 (Malvern instruments Ltd.). The samples were introduced in a beaker coupled with a Hydro Extended
148 Volume (EV), equipped with a dip-in centrifugal pump and a stirrer, until the desired obscuration level
149 (up to 20%) was reached. The dispersed sample then passed through the measurement area of the
150 optical bench, where a laser beam illuminated the particles. The obtained particle size distributions are
151 the average of 5 duplicate measurements.

152 **2.4. Falcon UF experiments**

153 The Falcon concentrator used in this work is a Falcon L40 laboratory model (Sepro Mineral
154 Systems, Canada). The device was operated in semi-batch and equipped with a 4" diameter ultrafine
155 (UF) smooth-walled bowl (Figure 3). During the tests, the Falcon was run at 63.89 Hz (200 G's) and
156 stopped at specific test durations, *i.e.* every 30 s for the first tests until 240 s and then at various
157 durations depending on the material, to recover both concentrate and tailings. When the particle size
158 distribution of the tailings was investigated, the Falcon was run continuously while tailings were
159 recovered in different sample collectors during the experiment to account for the tailings produced at
160 different duration of the experiment. Additional data from Filippov et al. [6], who investigated the
161 recovery of Light Rare Earth Elements (LREE) from kaolin residues using the same apparatus, was
162 used as a point of comparison. An overview of the materials and operating conditions for the

163 experiments can be found in Table 1.



164

165 **Figure 3.** Schematic cross-section of the Falcon L40 UF bowl modified after Refs. [6,22].

166

167 **Table 1.** Experimental design for the test series described in this study. For the St Austell tests, see Ref. [6].

Test series	Sample Type	Material				Operating conditions		
		D ₉₀ (μm)	Metal grade (%)	Host density (g.cm^{-3})	Gangue density (g.cm^{-3})	Rotary speed (G)	Pulp density (wt.%)	Flowrate (kg.min^{-1})
Altenberg	Greisen ore blend	78	~0.9	6.90	2.65	200	10	1.2
Tabuaço	Skarn ore	109	~0.5	6.00	3.4	200	11	1
FeSi	Synthetic ore	187	~24	6.53	2.7	200	2.5	3
St Austell 1	Kaolin residue	53	~0.04	5.15	2.6	200	10	1
St Austell 2	Kaolin residue (deslimed)	53	~0.04	5.15	2.6	200	10	1

168

169

170

3. EXPERIMENTAL RESULTS

171 3.1. Stationarity of separation performance with feed mass and time

172 Kinetic tests were conducted on all the samples with the Falcon UF by performing series of tests of

173 various durations, each time recovering the concentrate and tailings for mass balancing and assaying.

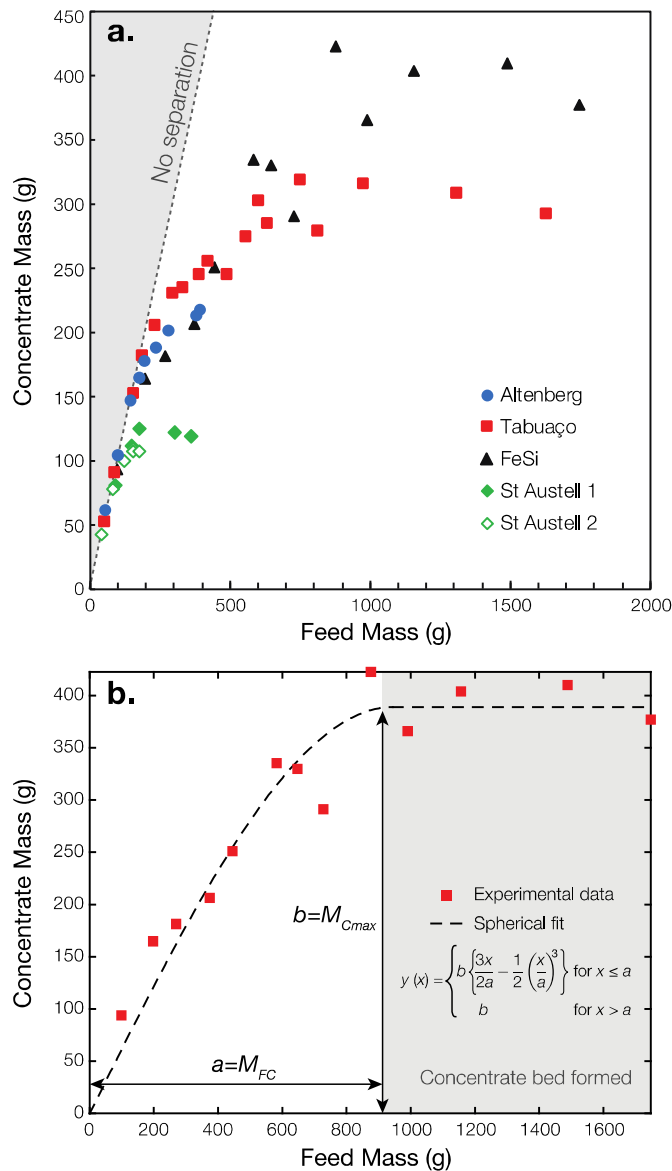
174 Figure 4a shows the evolution of the concentrate mass with the mass fed to the Falcon UF. All

175 materials display a similar trend to the one observed in Ref. [6]. First, an initial phase occurs during

176 which the concentrate mass is roughly equal to the feed mass, meaning that only desliming of the

177 extremely fine fraction happens. This phase is followed by an increase of the concentrate mass at a

178 reduced rate until a plateau is reached, indicating that the concentrate bed attains its final profile. It
 179 should be noted that for the Altenberg sample however, no plateau is clearly reached, suggesting that
 180 additional experiments would be required to reach the maximum concentrate mass. Estimates of the
 181 critical feed mass (M_{FC}), *i.e.* feed mass after which the concentrate bed is maximum, as well as the
 182 corresponding maximum concentrate mass (M_{Cmax}), are obtained by fitting a spherical model to the
 183 saturation curve (Figure 4b). This fitting procedure is only used as a rigorous way to characterise the
 184 critical feed mass of each material and will not be used for any modelling purposes whatsoever.
 185



186
 187 **Figure 4.** Determination of the maximum concentrate mass and corresponding feed mass. (a) Falcon UF
 188 concentrate mass as a function of feed mass for all materials. (b) Illustration of the fitting procedure (here for the

189 FeSi sample) used to characterise the maximum concentrate mass and corresponding critical feed mass for each
 190 sample.

191 The critical feed mass obtained for each material and corresponding maximum concentrate mass
 192 are given in Table 2. It can be seen that these values depend on the characteristics of the materials and
 193 are also likely to be impacted by the operating conditions of each series of tests. These values vary
 194 drastically with an order of magnitude of up to 6 between the fine and low-grade St Austell 2 material,
 195 which displays the smallest maximum concentrate mass of 107.7 g at a critical feed mass of only
 196 152.7 g, and the coarsest and highest-grade material, *i.e.* the synthetic iron ore (FeSi), which reached a
 197 maximum concentrate mass of 389.1 g at a feed mass of nearly a kilogram. The values given for the
 198 Altenberg sample are only indicative and may underestimate the maximum concentrate and
 199 corresponding critical feed mass as no clear plateau has been reached for this sample.

200
 201 **Table 2.** Estimation of the maximum concentrate bed, corresponding critical feed mass and curves fitting
 202 summary.

Tests	Unit	Altenberg	Tabuaço	FeSi	St Austell 1	St Austell 2
Critical feed mass (M_{FC})	g	311.6	488.3	944.3	188.6	152.7
Max. concentrate bed mass (M_{Cmax})	g	210.2	286.8	389.1	121.9	107.0
Max. Yield (M_{Cmax}/M_{FC})	%	67.4	58.7	41.2	64.7	70.1
R^2	-	0.99	0.94	0.93	0.97	0.99

203
 204 The critical feed mass obtained for each material can then be used to scale the results of each
 205 material by dividing the actual feed mass by the corresponding critical feed mass to reflect the bowl
 206 filling rate. A ratio of 100% corresponds to a feed mass equal to the critical feed mass, therefore
 207 suggesting that the concentrate bed reached its final profile and that the concentrate mass reached its
 208 maximum. It facilitates the comparison between the results from the different materials used in this
 209 study, regardless of their difference in terms of critical feed mass, and can be used as a reference to see
 210 the influence of the concentrate bed thickness on separation performance. The evolution of the Falcon
 211 UF separation performance in terms of enrichment ratio, yield and recovery with the % of critical
 212 mass (% M_{FC}) fed to the Falcon UF for all materials is shown in Figure 5a, 5b and 5c. Please note that
 213 enrichment ratio is used as a performance index instead of the concentrate grades as the latter vary
 214 drastically from one sample to the other (from hundreds of ppm for the St Austell sample to tens of

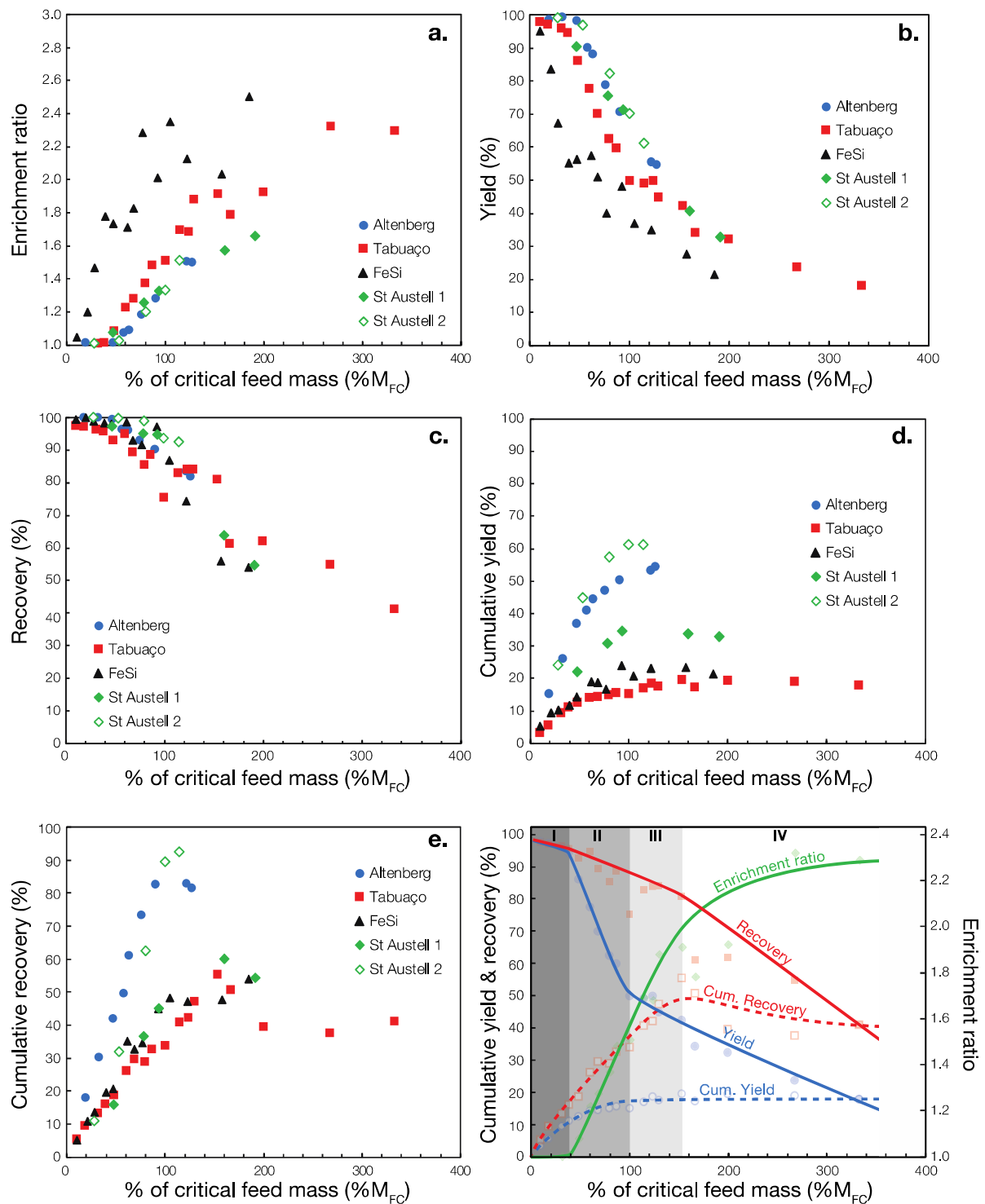
215 percent for the FeSi sample) making unpractical comparison between samples. For this reason, the
216 variability of the enrichment ratio, in particular for FeSi, may be due to experimental error caused by
217 slight variations in feed grade. For most materials, with the exception of the high-grade FeSi sample,
218 the enrichment ratio stagnates around one (*i.e.* no concentration) for the very low feed masses (below
219 50 wt.% of critical mass) and then steadily increases with increasing feed mass up to a maximum at
220 which it seems to reach a plateau (Figure 5a). On the contrary, the yield and recovery decrease with
221 increasing feed mass, first at a very low rate for the very low feed masses and then at higher rate with
222 an almost linear decrease (more important for the yield) until they suddenly break at distinct feed
223 mass. The yield decreases almost linearly (much more quickly for FeSi) until the critical mass is
224 reached and then decreases almost linearly again but at a lower rate than before the concentrate bed
225 was formed (Figure 5b). This last linear decrease cannot be observed for the Altenberg and St Austell
226 2 samples due to lack of data after 100% critical feed mass. The recovery continues to decrease after
227 the critical mass is reached until a certain feed mass depending on the characteristics of the material
228 and then decreases almost linearly again but at a higher rate than before (Figure 5c). The rapid
229 increase in enrichment ratio, as well as the rapid decrease in yield for the FeSi sample may be
230 explained by its relatively higher grade and higher degree of liberation of the heavy fraction
231 (theoretically 100%) compared to the other samples, as well as the high-density contrast between the
232 heavy and the light fractions.

233 Cumulative recovery (or yield), at a given time t (or feed mass), are calculated by taking as a
234 reference the last experiment (*i.e.* with the largest feed sample) of test duration $t=T$. Assuming that the
235 weights and grades of the concentrate obtained for tests of lower duration ($0 < t < T$) are representative
236 of the variation of concentrate weight and grade with time/feed mass during the last experiment,
237 cumulative recovery (or yield) would therefore reflects the kinetics of the separation. This is only an
238 approximation which should be kept in mind when comparing these “cumulative” indexes, *i.e.*
239 cumulative recovery/yield to the instantaneous ones, *i.e.* yield, recovery and enrichment ratios. The
240 evolution of the cumulative yield and recovery with the % of critical mass fed to the Falcon UF is
241 shown in Figure 5d and 5e. For all materials, cumulative yield increases with feed mass until it reaches
242 a plateau at 100% critical feed while cumulative recovery continues to increase up to a maximum and

243 then it seems to slightly decrease and to reach a plateau too.

244 These observations contradict the stationary separation assumption upon which the current physical
245 model is build. While previous works suggested the existence of three recovery phases [11,12], the
246 results obtained in this study exhibit four separation phases during a batch Falcon UF operation as
247 highlighted in Figure 5f using the results from the Tabuaço sample:

- 248 I. A first ineffective phase according to density for the first few tens of seconds of the operation
249 during which almost no concentration occurs, the concentrate bed quickly grows and only
250 differential settling impacts separation for the finest fractions which are ejected from the bowl
251 (this corresponds to the steady regime modelled in Ref. [14]).
- 252 II. A second phase during which enrichment and cumulated recovery both increase while the
253 cumulated yield quickly reaches a plateau, also highlighted by a break in the yield curve,
254 indicating that the concentrate bed reached its final profile.
- 255 III. A third stage during which enrichment and cumulated recovery continue to steadily increase up
256 to a point where cumulated recovery reaches a plateau, also indicated by a break in the recovery
257 curve while enrichment ratio stabilises more gradually with increasing mass processed until it
258 also reaches a plateau when the concentrate bed is saturated. This more gradual increase of the
259 enrichment ratio compared to cumulative recovery is attributed to the aforementioned
260 approximation used to calculate cumulative recovery as well as potential experimental errors
261 associated with the enrichment ratio, as mentioned before.
- 262 IV. A fourth stage at which cumulative recovery, cumulative yield, and enrichment ratio stagnate,
263 indicating that no more separation occurs and that the concentrate bed is saturated while yield
264 and recovery continue to decrease, the latter at a more important rate than the yield, until
265 ultimately reaching a near-zero value for very large feed masses, as observed by Ref. [12].



266

267 **Figure 5.** Effect of % of critical feed mass ($\%M_{FC}$) on Falcon UF separation performance. (a) Enrichment ratio,

268 (b) Yield, (c) Recovery, (d) Cumulative yield, (e) Cumulative recovery and (f) Overview for the Tabuaço sample

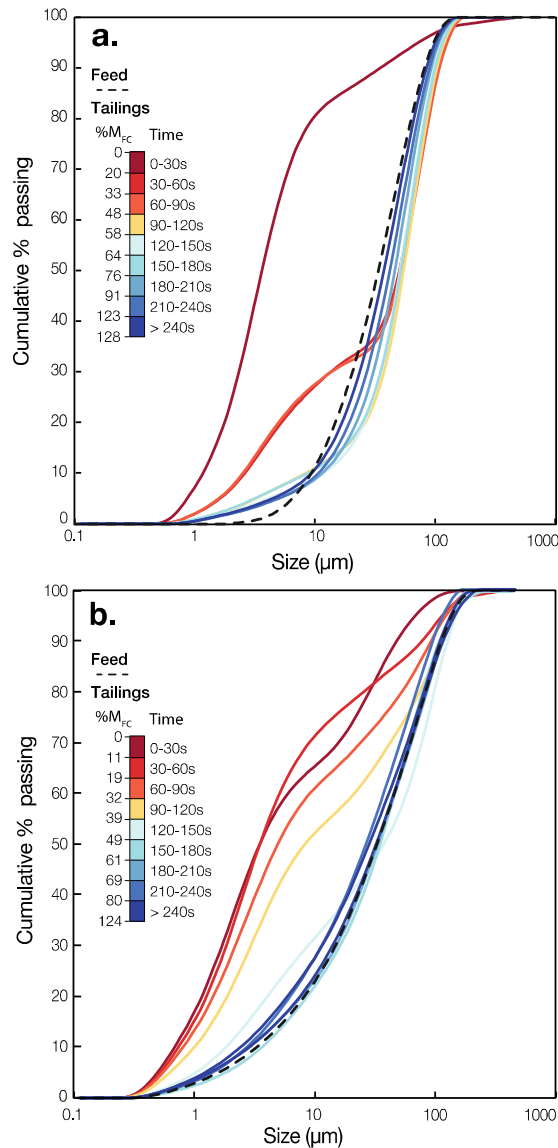
269 with trend lines and identification of the distinct phases of the separation (see text for details).

270 3.2. Particle size effects

271 Additional tests were conducted, this time following the evolution of the particle size distribution
272 (PSD) of the Falcon UF tailings with time for the Altenberg and Tabuaço samples (Figure 6). Results
273 suggest that, during the first phase of the separation, mostly ultrafine ($-10\ \mu\text{m}$) particles are rejected.
274 After about 90-150s, depending on the material, corresponding to around 50% of critical feed mass
275 *i.e.*, during the second phase of the separation, the tailings display a much coarser PSD, which slightly
276 translates towards the finer size ranges. It is clearly visible for the Altenberg sample, until its PSD
277 becomes similar to the feed material PSD, when the concentrate bed reached its final profile at the
278 beginning of the third phase of the separation.

279 These results confirm those obtained by Kroll-Rabotin et al. (2012) with pure quartz, who showed
280 that the tailings PSD remains unchanged for the first few minutes of the separation and then shifts
281 towards the PSD of the feed [22]. This first phase of the separation during which ultrafine particles are
282 rejected with a relatively constant PSD was taken to be a proof that the Falcon UF operates a steady
283 state separation until the retention zone is full [22]. While it may be true for pure minerals, it seems
284 that the opposite is observed here with more complex materials such as the industrial ores used in this
285 study, exhibiting more heterogeneous compositions comprising high density metal-bearing minerals
286 and gangue minerals displaying a range of low to medium specific gravities (Table 1). The first phase
287 of the separation is actually non-selective from a metal-concentration point-of-view and only
288 corresponds to a desliming phase during which the concentrate bed is still building up. The sudden
289 increase in tailings PSD while cumulative recovery and enrichment ratio continue to increase could be
290 evidence that actual gravity concentration still occurs after the bed is fully formed and that the effect
291 of particle size becomes more limited.

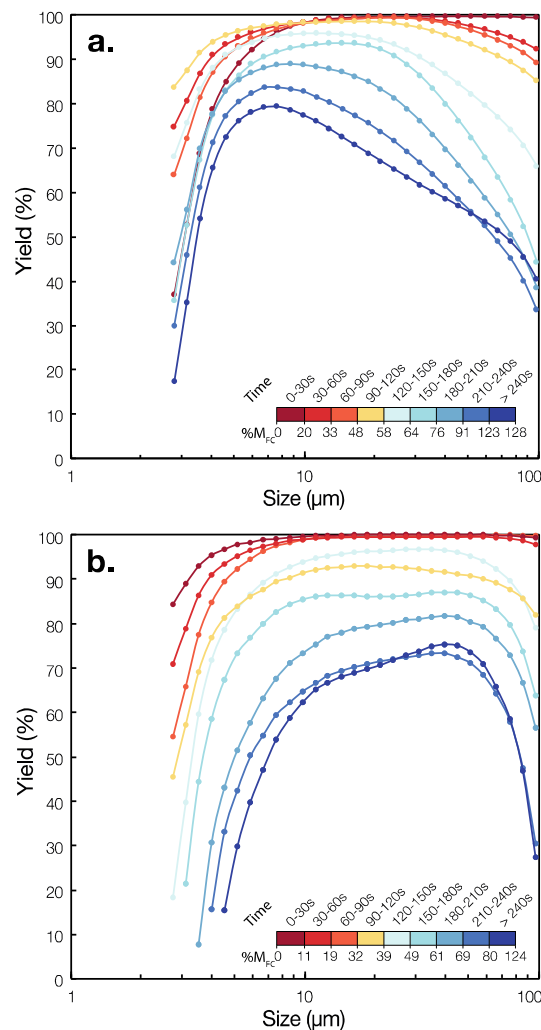
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293
 294 **Figure 6.** Variation over time and % of critical feed mass (%M_{FC}) of the particle size distribution of the tailings
 295 of the Falcon UF concentrator for the Altenberg (a) and Tabuaço (b) samples.
 296

297 Considering that the PSD of the feed remains constant during the experiment, the PSD of the
 298 tailings, along with the yields given in Figure 5, can be used to calculate the partition curve, *i.e.* the
 299 yield per size fraction, as a function of time for the Altenberg and Tabuaço samples (Figure 7). As
 300 expected, at the beginning of the operation, ultrafine particles ($\sim 5 \mu\text{m}$) are ejected from the bowl. The
 301 concentrate bed is forming, the size recovery curves display a slightly decreased coarse particles
 302 recovery. These coarse particles losses drastically increase once the concentrate bed is formed,
 303 especially for the Altenberg sample. On the contrary, recovery at intermediate particle sizes, around 5-
 304 20 μm for Altenberg and 10-60 μm for Tabuaço, is higher during the whole operation. These features

305 are not without reminding those observed with spiral concentrators [23,24]. In such devices, the
 306 decrease in coarse particles recovery is attributed to the Bagnold force that preferentially flushes
 307 coarse particles towards the outer zone of the spirals through [25–27]. However, in the present study,
 308 the coarser size fractions are also depleted in dense particles as most of the tin and tungsten are
 309 distributed in the finer size fractions for the Altenberg and Tabuaço samples, respectively (Figure 2),
 310 which correspond to the size ranges of highest recovery when the concentrate bed is formed for both
 311 samples (Figure 7). Similar behaviour was observed by Laplante and collaborators processing gold ore
 312 flotation feed [12]. However, the same authors also reported the opposite behaviour using a Falcon B6
 313 with synthetic magnetite-silica or gold-pyrite systems with a U-shaped partition curves for dense
 314 particles, *i.e.* lowest recovery at intermediate particle sizes [11,12].
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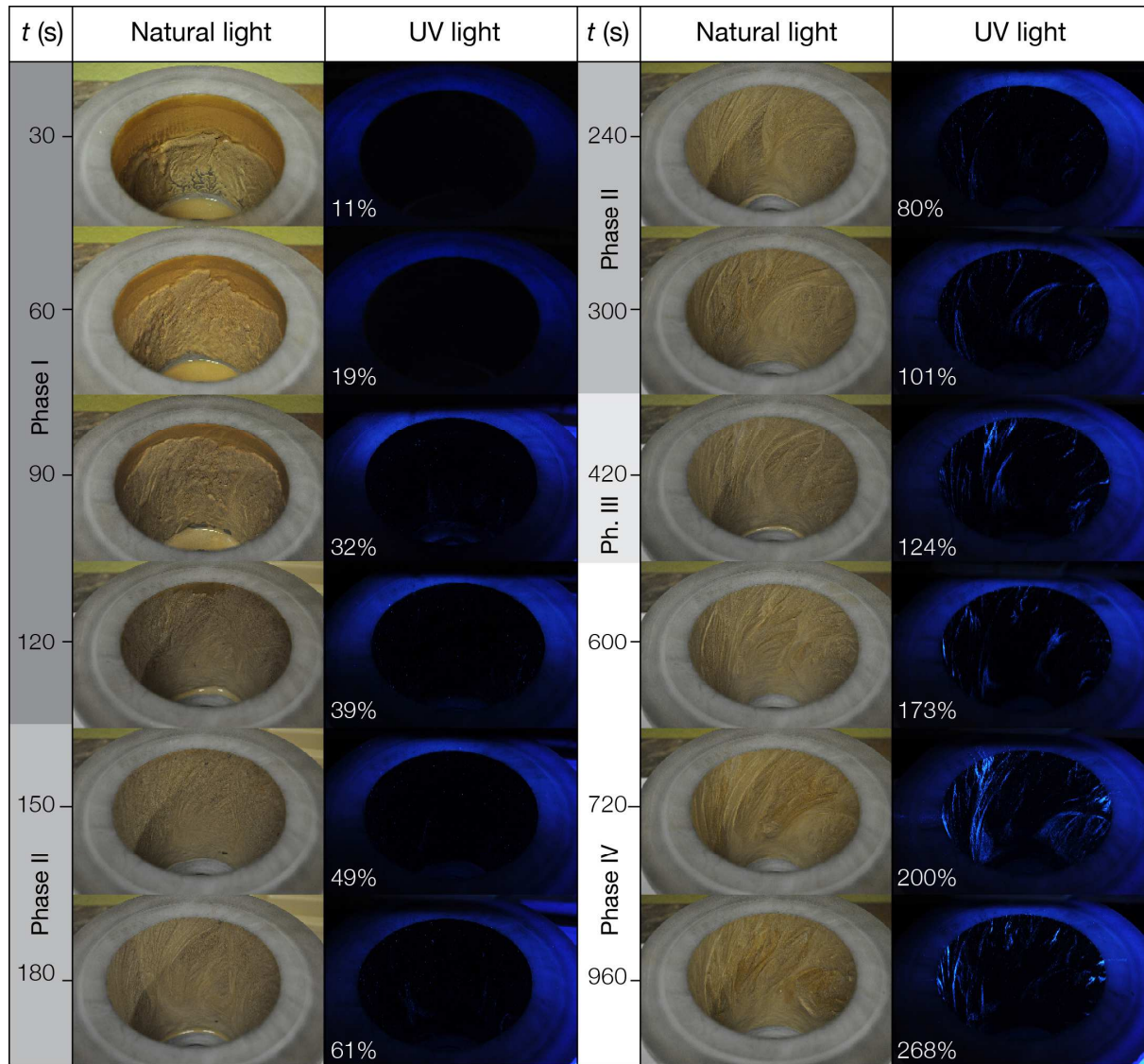


316
 317 **Figure 7.** Variation over time and % of critical feed mass ($\%M_{FC}$) of the partition curves of the Falcon UF
 318 concentrator for the Altenberg (a) and Tabuaço (b) samples.

319 **3.3. Observations of the evolution of the concentrate bed during the operation**

320 An examination of the Tabuaço concentrate bed within the Falcon UF bowl has been performed by
321 marking the four cardinal points of the bowl and stopping the Falcon at different times. Figure 8 shows
322 photographs of the concentrate bed at different times of the separation, *i.e.* at different % of critical
323 feed mass, always pointing towards the same direction, with natural or ultraviolet (UV) light to reveal
324 scheelite particles which fluoresce under short-wavelength UV light. It reflects the evolution of the
325 concentrate bed during the four above-mentioned separation phases defined in Figure 5f. After 150 s,
326 at 49% critical feed mass, phase II has just started, the concentrate bed is not yet completely formed
327 and no clear concentration of scheelite is observed but rather some disseminated sparks, reflecting the
328 composition of the feed. At 300 s, *i.e.* 101% critical feed mass, which corresponds to the transition
329 between phase II and III, the concentrate bed has now reached its final profile and concentration of
330 scheelite is clearly observed. Some erosion figures start to appear on the bed surface and observations
331 under UV light suggest that scheelite is concentrated within these furrows. After 600 s, *i.e.* 173%
332 critical feed mass, the furrows have changed positions indicating a local dynamic with erosion figures
333 which are likely to evolve with time. From 720 s, *i.e.* 200% critical feed mass, some scheelite grains
334 are observed on the edges of the bowl indicating scheelite losses to the tailings. The observed erosion
335 figures correspond to the so-called furrows observed by Buonvino with a synthetic iron ore [11].
336 These furrows are created by the action of the slurry through the concentrate bed during its upward
337 flow and, hence, may indicate preferential flow areas. This picture proves that the furrows actually
338 play an active role in the separation as scheelite seems to be preferentially concentrated only within
339 these furrows.

340



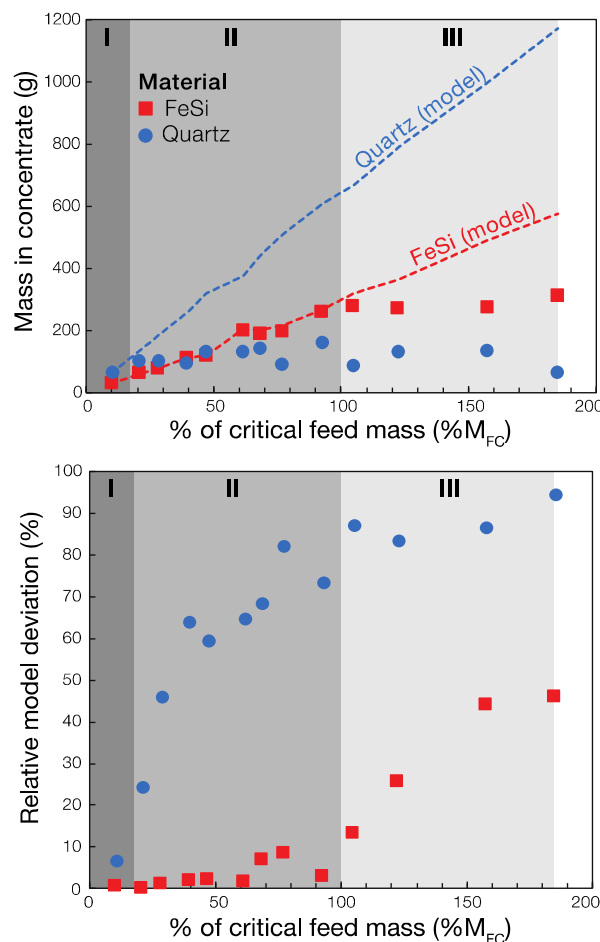
341
 342 **Figure 8.** Photographs of the Tabuaço Falcon UF concentrate bed at different times of the separation or % of
 343 critical feed mass (non-linear scale) under natural or UV light with corresponding phases of separation as
 344 delimited in Figure 5f. All photographs are taken from the same angle, looking at the same direction.

345

346 4. IMPLICATIONS FOR THE FALCON UF PHYSICAL MODEL

347 The synthetic iron ore being constituted of set proportions of pure quartz and FeSi, the density and
 348 particle size distribution of which are known (see Table 1), the washability of this sample is thus fully
 349 characterised. Since the experimental conditions at which the Falcon UF tests were conducted are also
 350 known, it is possible to predict the recovery of both quartz and FeSi as well as their corresponding
 351 quantity in the concentrate using the current predictive model presented in Eq. (1). These values can
 352 then be compared with the mass of quartz and FeSi in the concentrate measured experimentally which

353 are easily obtained by recovering the FeSi particles with a magnet. Comparison of experimental and
 354 predicted quartz and FeSi masses in the concentrate shows that the predicted masses do not fit the
 355 experimental data for quartz and only partially until the last third of phase II for FeSi (Figure 9a).
 356 Indeed, from the first test, the relative model deviation for quartz sharply increases to reach up to 90%
 357 relative deviation while for FeSi, the relative model deviation stays below 10% for the first 7 tests
 358 (Figure 9b).
 359



360
 361 **Figure 9.** Comparison between experimental and predicted results for ferrosilicon (FeSi) and quartz using the
 362 Falcon UF physical model in Eq. (1) for the synthetic iron ore. (a) Predicted (dashed line) and observed
 363 (points/squares) concentrate mass as a function of %M_{FC}. (b) Relative model deviation compared to
 364 experimental results as a function of %M_{FC}.

365
 366 From Figure 5 to 9, it can be inferred that two separation mechanisms are at play. The differential
 367 settling of particles within the flowing film is the one mechanism that has been accounted for in the

368 model developed by Kroll-Rabotin et al. [22], which is responsible for the ejection of fine particles
369 during the whole separation cycle. However, the non-uniform decrease of the yield after the
370 concentrate bed results from another mechanism. Hence the existing physical model should be valid
371 for phase I and partially phase II as observed for FeSi in Figure 9. To fully account for phases II and
372 III, another physical mechanism must be considered to explain how particles that have reached the bed
373 (seen as trapped by the current model) may or may not be resuspended. Even, if the model seems to
374 also apply to stage II for the FeSi, this is probably an artefact due to its very narrow size and density
375 distributions.

376 Though the second mechanism does not achieve a steady state separation, it has been observed on
377 Figure 9 that it is more sensitive to particle specific gravity and less to particle size compared to
378 differential settling, and thus it improves the separation. This may be explained by the role of the lift
379 force (F_L) that has been neglected in the physical model presented in Eq. (1). Indeed, when coarse
380 particles reach the bed, the model assumes that they stay in it. Nevertheless, a fixed particle at the
381 surface of the bed experiences a non-negligible slip velocity compared to the fluid, which, in
382 combination with very high local shear rate, results in a potentially significant lift force when the
383 flowing film is very thin, that is when the retention zone is filled. Lift force models for particles close
384 to a wall are available in the literature, but with very large differences in terms of particle size
385 contribution depending on the authors (exponents varying from 1.87 to 4 in the models listed in Ref.
386 [28]), showing that the derivation of quantitative recovery models based on this force is still an issue.
387 After listing many lift force models from the literature, Zeng et al. [28] provided their own, derived on
388 numerical simulations of spherical particles close to a smooth wall. Although this situation is very
389 idealistic compared to the mineral particles depositing in the retention zone of a Falcon concentrator, it
390 gives a first approximation of the lift force undergone by the particles at the surface of the bed and
391 how this force is impacted by the operating parameters. The lift force model by Zeng et al. [28] takes
392 the following form:

$$F_L = 4.24 \rho_f v^2 \left(\frac{1}{2} d_p \left(\frac{\gamma}{v} \right)^{1/2} \right)^{3.12} \quad (2)$$

393 where most parameters already appear in Eq. (1) and γ is the wall shear rate. Considering that this
394 force mainly opposes particle apparent weight, and that the wall shear rate can be estimated from the
395 analytically approximated velocity profile used in derivation of Eq. (1) [19], it yields a criterion to
396 decide whether a given particle is able to stay immobile at the surface of the concentrate bed. A more
397 detailed derivation of this criterion is provided in Appendix A. When lift force prevails over apparent
398 weight, there is no equilibrium for such particles at the bed surface, which means that they either slide
399 or roll on the bed surface or get transported by the flow and end-up being removed from the
400 concentrate bed. This criterion can be turned into a very simplified separation curve, in the form of a
401 cut surface, taking the value 1 when the particle stay at the surface of the concentrate bed and 0 when
402 the particle is resuspended, the derivation of which can be found in appendix:

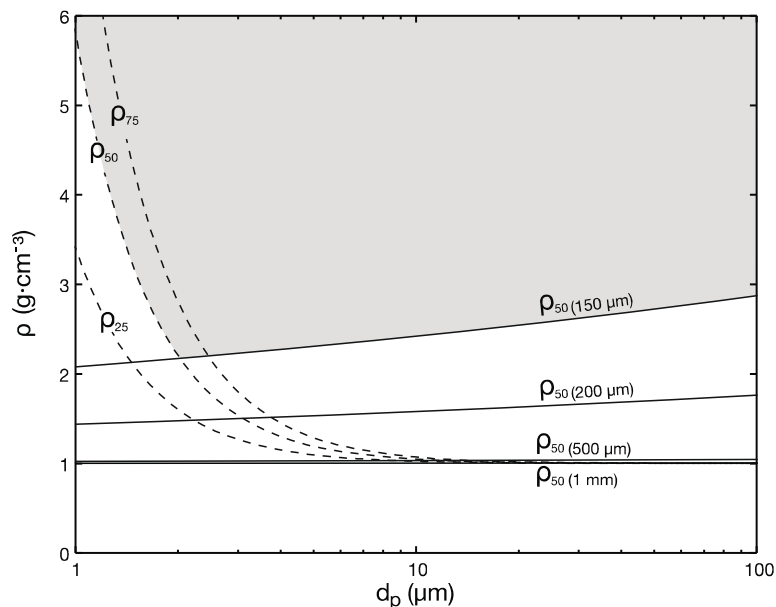
$$C_p^L = \begin{cases} 1, & \rho_p > \rho_f (1 + 0.294 \nu^{0.44} Q^{1.56} \omega^{-2} d_p^{0.12} R_{max}^{-2.56} h_{film}^{-3.12}) \\ 0, & otherwise \end{cases} \quad (3)$$

403 This separation curve has two noteworthy features. Firstly, the value of the cut density depends
404 only very little on particle size (d_p has exponent 0.12), which means that the resuspension mechanism
405 achieves a mostly density-based cut that is much less impacted by particle size than differential
406 settling. Secondly, separation is strongly dependent on film thickness (h_{film}), which, in this part of the
407 bowl, is directly related to the volume of concentrated material. As a consequence, separation
408 according to this resuspension criterion varies during the operating cycle, as observed by Laplante et
409 *al.* [12] and in section 3, unless the film thickness is controlled. This explains the observation and
410 solution developed by Deveau [18] using an adaptive lip at the top of the bowl that grows during the
411 separation cycle and maintains a more constant film thickness over time in the retention zone to
412 control the separation while the bowl gets filled with concentrate.

413 Figure 10 shows the density cuts from the differential settling separation (C_p) defined in Eq. (1) and
414 the lift induced separation (C_p^L) defined in Eq. (3) for various film thicknesses. The maximum realistic
415 value for this thickness is a few millimetres, which is the depth of the retention zone when the bed is
416 empty, at the beginning of an operating cycle. Its minimum value is the one of the flowing film flow
417 induced by the fast rotation of the bow, which has been observed to go as low as 100 μm in the
418 operating conditions of a laboratory scale Falcon UF [19]. The data in Figure 10 correspond to a

419 Falcon L40 unit that is not equipped with a varying lip retention zone. Figure 10 shows that the
 420 differential settling cut (in dashed line) is constant during a separation cycle but selective entrapment
 421 in the bed (continuous line) is not. As the retention zone gets filled with concentrate, the flowing film
 422 thickness decreases and the value of the cut density increases. The separation behaviour is thus
 423 transient and cannot be represented with a single cut surface. Future model developments will thus
 424 require a dynamic model. As a preliminary interpretation guide, Figure 10 shows a cut surface in grey
 425 colour that corresponds to the quasi static separation regime when the film is 150 μm thick. It means
 426 that when the bed is 150 μm thick, particles bigger than 10 μm with a density below approximately 2.5
 427 $\text{g}\cdot\text{cm}^{-3}$ (below the grey area) will not be trapped, and that if such particles were trapped before and
 428 were close to the bed surface, they would be resuspended in the flow, which would in turn modify the
 429 height of the trapped bed and the film thickness. A very interesting result in regard to the performance
 430 of Falcon UF separation units is that the resuspension mechanism favours recovery of small particles
 431 with high density, as long as they are big enough not to be rejected due to the settling criterion. This is
 432 a strong asset to recover ultrafine particles compared to most other separation methods in which both
 433 density and size have a positive effect on recovery.

434



435

436 **Figure 10.** Cut functions corresponding to the differential settling mechanism (dashed line) and lift effect (solid
 437 line) for different flowing film thicknesses (in brackets). The two models are respectively defined in Eq. (1) and
 438 in Eq. (3), and are evaluated for a Falcon L40 with UF bowl operated at similar conditions to the FeSi

439 experiments, *i.e.* $Q = 3$ l/min and $\omega = 1863$ rpm (*i.e.*, 200 G).

440

441 The data presented in Figure 10 should not be read as quantitative, since the lift model by Zeng et
442 al. [28] is only one among many and corresponds to an idealised case compared to the Falcon UF
443 concentrate bed surface. For instance, the Bagnold effect is another way to explain the hydrodynamic
444 lift experienced by particles under the influence of nearby boundary, fluid shear, and particle spin,
445 which preferentially lifts particles into the higher velocity zones of the flowing film and that has more
446 commonly been used to understand physical separation within gravity concentrators [26,29]. A
447 discussion on the Bagnold force and how it compares to the lift force used here is provided in
448 Appendix B. A quantitative model would need to integrate the evolution of the concentrate bed
449 content over time and to be calibrated by experimental data. Moreover, when the flowing film
450 becomes thin enough for resuspension to happen, its thickness gets close to the size of the resuspended
451 particles, so a simple lift force model is not expected to capture the whole resuspension dynamics
452 without corrective terms that will need to be calibrated from experiments. However, the simple
453 resuspension criterion presented here gives a very interesting guide on what physics are at play and
454 perform the separation in a Falcon UF bowl, for denser materials than the ones originally studied by
455 Kroll-Rabotin et al. [19–22]. It provides a nice physical explanation to the experimentally observed
456 improvement of the separation when the retention zone gets filled.

457

458 The four phases observed in section 3.1 can thus be interpreted as:

- 459 I. When the bed is not formed, the separation starts by a desliming-only phase that is controlled by
460 differential settling in the flowing film;
- 461 II. As the concentrate bed grows, the flowing film gets thinner and shear increases in the flow,
462 which makes particles at the surface layer of the bed undergo a lift force that is able to resuspend
463 them into the tailings stream. The balance between this lift force and the enhanced gravity tends
464 to suspend coarser and less dense particles first. During this phase, separation evolves from a
465 differential settling driven selection to a resuspension driven selection;
- 466 III. When the bed is fully formed, the flowing film is very thin and highly sheared so that selective

467 erosion of the bed is strong and concentrate grade continues to increase although the mass of
468 concentrate remains constant. During this stage, dense and fine particles enter the retention zone
469 as coarser and less dense particles make room for them while being resuspended. This leads to
470 the emergence of furrows of higher-grade material at the surface of the bed;

471 IV. As the surface layer of the bed contains higher-grade material and less gangue, the resuspension
472 mechanism ejects more and more dense particles, until it balances the stream of particles settling
473 at the bed surface and separation finally drops as the bed is saturated.

474 During all four stages, deposition of particles onto the bed is always governed by differential settling,
475 which does not depend on the flowing film thickness [14], so that desliming of ultrafine particles stays
476 the same.

477

478

5. CONCLUSIONS AND PERSPECTIVES

479 This experimental investigation into the kinetics of Falcon UF concentration contradicts the
480 stationarity and the no-resuspension hypotheses on which the existing physical model is based. The
481 evolution of Falcon UF performance indexes suggests a 4-phases separation. A first phase during
482 which a bed quickly grows unselectively while ultrafine particles are ejected from the bowl. Then, a
483 second phase where selective separation starts by differential settling while the concentrate bed
484 quickly grows until it reaches its final profile. Next, a third phase starts, while the concentrate bed
485 stabilizes, recovery and enrichment continue to increase through selective erosion phenomenon that
486 seems to favour the concentration of dense particles. Finally, during the fourth stage, capture sites
487 saturate and recovery drops. These results, combined with the evolution of partition curves over time,
488 suggest the existence of two separation mechanisms: (i) differential particles settling within the
489 flowing film responsible for the ejection of fine particles during the whole separation cycle which is
490 already accounted for in the physical model, and (ii) resuspension of particles from the concentrate
491 bed which may be explained by the action of lift force, neglected in the existing physical model. This
492 force acts preferentially on coarse particles deposited at the surface of the bed, resulting in these
493 particles being rejected in the tailings.

494 The addition of a lift force component to the existing model is discussed and a resuspension
495 criterion is proposed as a guidance of the physics involved in this second separation mechanism.
496 However, the future developments will require a dynamic model which would need to integrate the
497 evolution of the concentrate bed content over time and to be calibrated on experimental data.

498

499

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508

509

APPENDIX

Appendix A: Derivation of the resuspension criterion

511 Particle resuspension at the wall has been modelled (cf. Section 4) based on the expression of a lift
512 force (F_L) from Ref. [28] and defined in Eq. (2), acting on a static particle deposited on a smooth wall.
513 Such a lift force opposes the apparent weight of particles that results from the centrifugal force (F_C)
514 and the buoyancy force (F_B) due to the density difference between the particles and the fluid (Figure
515 A1):

$$F_C = \frac{\pi}{6} d_p^3 \omega^2 R_{max} \rho_p \quad (4a)$$

$$F_B = \frac{\pi}{6} d_p^3 \omega^2 R_{max} \rho_f \quad (4b)$$

516 A resuspension criterion for a given particle can then be written in the form of a cut surface, taking
517 the value 1 when the particle stays at the surface of the concentrate bed and 0 when the force balance
518 on the particle at the bed surface does not allow it to stay deposited. This can be summarised by the

519 following expression:

$$C_p^L = \begin{cases} 1, & F_L + F_B < F_C \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

520 The cut surface for the resuspension criterion can then be expressed based on particles density:

$$F_L + F_B < F_C \Leftrightarrow F_L < \frac{\pi}{6} d_p^3 \omega^2 R_{max} (\rho_p - \rho_f) \quad (6)$$

$$\Leftrightarrow \rho_p > \rho_f \left(1 + 6 \frac{4.24}{\pi} \frac{1}{2^{3.12}} \frac{v^2}{\omega^2 R_{max}} d_p^{0.12} \left(\frac{\gamma}{v} \right)^{1.56} \right) \quad (7)$$

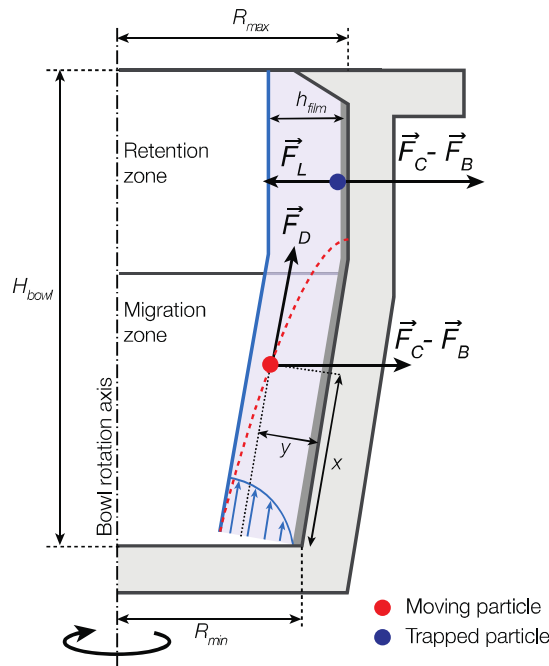
521 Where the wall shear rate (γ) can be estimated from the analytical velocity profile used in derivation of

522 Eq. (1), using the approximation of a Poiseuille flow in the thin film flowing on the particle bed [19]:

$$\gamma = \frac{3}{2} \frac{Q}{2\pi R_{max} h_{film}} \frac{\partial}{\partial y} \left(1 - \left(\frac{y - h_{film}}{h_{film}} \right)^2 \right)_{y=0} = \frac{3}{2} \frac{Q}{\pi R_{max} h_{film}^2} \quad (8)$$

523 where y is the normal distance of the particle from the wall (Figure A1).

524



525

526 Figure A1. Schematic cross section of the Falcon UF bowl showing the main forces controlling particles

527 trajectory, *i.e.* the drag force (F_D), the centrifugal force (F_C), the buoyancy force (F_B) and the lift force (F_L),

528 modified after Ref. [20].

529

530 Using the above definition for the wall shear rate, the cut density for the resuspension can then be

531 defined by the following expression:

$$\rho_p > \rho_f \left(1 + 6 \frac{4.24}{\pi^{2.56}} \left(\frac{3}{2} \right)^{1.56} \frac{1}{2^{3.12}} \nu^{0.44} Q^{1.56} \omega^{-2} d_p^{0.12} R_{max}^{-2.56} h_{film}^{-3.12} \right) \quad (9)$$

$$\Leftrightarrow \rho_p > \rho_f (1 + 0.294 \nu^{0.44} Q^{1.56} \omega^{-2} d_p^{0.12} R_{max}^{-2.56} h_{film}^{-3.12}) \quad (10)$$

532

533 It makes sense that the value of the density has a weak dependency on particle size, since the
534 Falcon concentrator is a gravity-based separator and, as such, its separation principle is expected to be
535 mostly sensitive to particles density rather than their size.

536

537 **Appendix B: Discussion on the Bagnold force**

538 The latter expression can be compared to Bagnold's formula for particle erosion due to saltation
539 [30,31]. First, it is important to note that Bagnold's effect has been quantified from empirical results as
540 a particle resuspension flux [26]. Defining such a flux would be useful to characterise the separation,
541 but it does not fit well in the currently existing model that is expressed as a steady cut surface. A
542 transient model will be necessary in the longer run since transient behaviour has been experimentally
543 observed, but it will be a major evolution of the current model that will require its own set of
544 experiments for calibration. Now, assuming that a direct relation exists between Bagnold's
545 resuspension flux and the aforementioned resuspension criterion, the overall trends would be
546 consistent: dependence on size has an exponent of 0.12 while Bagnold force expression would give a
547 value between 0 "when the effects of fluid viscosity dominate" and 2 in turbulent transport [31,32]
548 whereas the dependence on shear rate has an exponent of 1.56 while Bagnold's would be between 1
549 and 2 in the same respective flow conditions [31,32].

550 However, the resuspension criterion described in Eq. (3) is based on a static force balance on a
551 deposited particle at the surface of the concentrate bed, while Bagnold's formula is empirical and
552 accounts for erosion that is a combined effect from several mechanisms. Moreover, the Bagnold effect
553 can vary significantly under different conditions and may not apply to particles deposited at the
554 surface of the concentrate bed of a Falcon UF. Firstly, the apparent particle weight: in most Bagnold's
555 derived erosion expression, particles are expected to be transported by the flow. In the situation of

556 very high gravity field, it is unlikely that so-called “resuspended” particles are actually transported in
557 the film, they most probably slide or roll on the bed surface since the force balance does not allow
558 them to stop at its surface. Secondly, the suspension rheology: Bagnold’s effect assumes that there is a
559 layer of solids flowing with the film in which collisions between the solids transfer stresses that are
560 accounted for by an apparent rheology of the multiphase mixture. In a Falcon UF, if particles are not
561 really resuspended but rather unable to remain at bed surface, there is no evidence that such a layer of
562 solid-liquid mixture is flowing at the top of the bed. In addition, in the case of Falcon UF operation,
563 the film Reynolds number is moderate, meaning that there is no turbulence to achieve dispersion of the
564 solids in the film, and the gravity field is high, which means that settling prevails in the particle
565 dynamics unless particles are stuck at the bed surface.

566

567

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Phases of separation:

- I. Desliming: Differential settling only
- II. Differential settling > Resuspension
- III. Resuspension > Differential settling
- IV. Saturation

