

1 **Ore types: what they are, how they're made, and their uses and abuses**

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8

9 **Abstract**

10 Prior to mining, all rocks contained in a mineral deposit must be placed in one of several
11 categories known as ore types. Each ore type describes a different way that the rock will behave
12 in processing. The ore type determines which process stream a particular mined unit will be sent
13 to, sets expectations for process engineers and metallurgists, and forms the basis for recovery
14 predictions and production estimates.

15 Ore types are assigned mainly by geologists based on visible geological criteria (dominant
16 ore mineralogy, estimated grade, rock type, alteration type). As metallurgical tests are carried out
17 and process data accumulate, the resulting criteria may be factored into the ore typing process,
18 typically as assays and recoverable metal using the relevant process(es). Other variables may
19 also be incorporated into ore typing at operations if they are particularly important, such as
20 grindability, preg-robbing, gangue reagent consumption, and the presence of especially
21 deleterious minerals such as talc or smectite. The mine operations department may also redefine
22 ore types and/or process destinations based on economic criteria. A “best” ore type is designated
23 that (in theory) best describes how the rock will behave in processing. Codes representing this

24 ore type are entered into the drill hole database, then interpreted on cross sections and level
25 plans, and finally added to the block model. Ore types are iteratively reexamined and adjusted
26 over the life of a project. Major difficulties in effective ore typing are (1) lack of communication
27 between geologists and metallurgists; (2) the imprecision inherent in imposing clean categories
28 on messy natural systems without discrete divisions; (3) the need for ore types to provide useful
29 information for a wide range of processes; (4) difficulties in scaling up laboratory test results to
30 mine production; and (5) conflict among geological, metallurgical, and economic criteria for ore
31 typing.

32

33 **Definition and function of ore types**

34 The fate of any rock in a mine is predetermined before the shovel touches it. It has already
35 been classified as a particular *ore type*, a numerical tag that describes what path it will be routed
36 on: waste, mill, leach, stockpile, etc. The ore type serves as a guide to what operations will be
37 performed, how much recovery can be expected, what operating parameters will yield the best
38 results, and what problems will be caused and how to mitigate them, throughout the long process
39 of extracting the metal contained in that rock and millions of tons of others assigned to the same
40 ore type. Correct ore typing results in performance meeting expectations; bad ore typing causes
41 drops in mill recovery, flotation cells overflowing, ores failing to leach, and a multitude of other
42 sudden and unanticipated problems in processing.

43 The ideal ore type is a category of material that:

- 44 • All behaves the same way during extractive processes, and
- 45 • Behaves differently from materials in all other ore types in one or more important
- 46 ways.

47 In general the difficulty of assigning ore types increases in proportion to the number of major
48 ore minerals, the number of different rock types, and the size of the mine. In the simplest cases, a
49 mine with only one process option (e.g. dump leach) may limit its ore typing to distinguishing
50 between ore and waste. However, this tends to lead to less-than-optimal economics since
51 blending and adjustments to operational parameters are ad-hoc if they happen at all. More
52 commonly, a small mine on a simple ore deposit might have three or four ore types based only
53 on grade and ore mineralogy. A large, complex, and long-lived mine could have 20 plus assorted
54 subvariants and include characteristics such as grindability and smectite content.

55 The distribution of ore types across the deposit is mapped in the block model and factors into
56 the mine plan. When a block is blasted and excavated, its ore type is used to route it to waste, to
57 the crusher, to leaching, or to the appropriate stockpile. If the operation requires blending, ore
58 typing determines the proportions of ingredients to be mixed. Ore types, including rock and
59 alteration data, are used to determine operational parameters for each part of the process. The
60 assessment of ore types, and the assignment of every rock in a mine to one of them, is thus
61 ubiquitous in mining and vital throughout the value chain.

62

63 *Need for empirical determination of ore types*

64 A great deal of labor, time, and Tylenol would be saved if it were possible to predict an ore's
65 behavior simply from its rock type and mineralogy. Instead of spending weeks on Bond work
66 index tests, a metallurgist could simply look up the Bond index of strongly serpentinized
67 andesite, or the leach recovery and reagent consumption of a chrysocolla-dominated mixed ore
68 suite, in a reference table. In practice, most ore types designated by this method would be
69 useless. Tabulated values for even the simplest parameters vary by factors of two for what is

70 allegedly the same rock type, and most descriptions are not detailed enough to sort out the
71 specific effects of weathering, variation in grain size, differences in modal mineralogy, textural
72 differences, and so on. Each rock and each mine are so different from others of the same nominal
73 type that there is no alternative to testing the specific rocks at the specific mine to determine their
74 relevant characteristics.

75 Because of its importance and labor-intensity, the ore typing process is a major investment
76 for mining companies. Good or bad ore typing can have a profound impact on the eventual
77 profitability (or not) of the mine. Yet despite this, ore typing is seldom discussed in the
78 professional literature, most of which is written by academics without access to the necessary
79 samples or data. Jackson and Young (2016) and Lishchuk et al. (2020) provide some of the few
80 reviews available, and Cropp et al. (2014) describes the integration of ore typing information
81 across the mining value chain. Some other information about ore typing at specific mines can be
82 gleaned from various SEC 10-K and NI 43-101 reports. Otherwise the literature about ore typing
83 is as scanty as the practice is common.

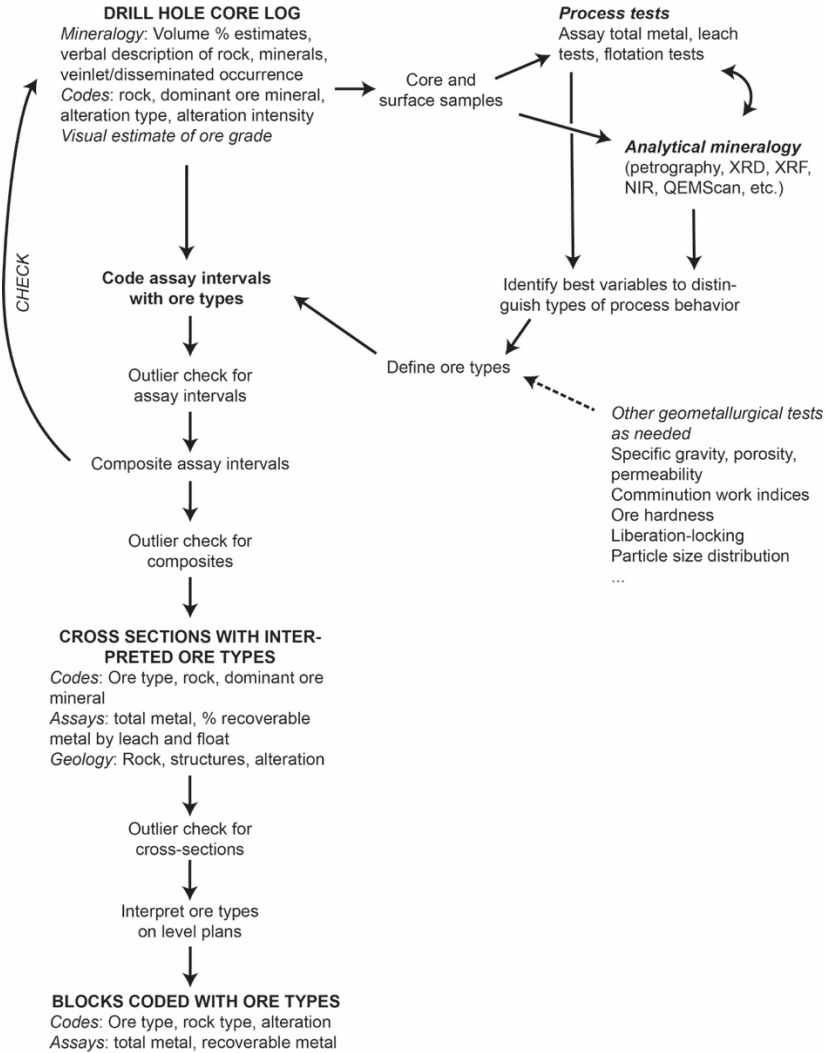
84

85 **The process of ore typing**

86 *Workflow and stages*

87 Typically ore typing begins during the late exploration or early development stage of the
88 mine lifecycle. Some of it is intrinsic to the exploration process, since whether its contained
89 metal is economically recoverable or not determines whether a volume of rock is an ore deposit
90 or just a geochemical anomaly. Exploration geologists therefore pay attention not only to
91 estimated metal grade, but to the ore mineralogy, grain size, and other characteristics that will

92 eventually factor into recovery. The overall ore typing process, from start to finish, is shown in
 93 Figure 1.



94
 95 Figure 1. Schematic flow chart of how ore types are devised and incorporated into the block
 96 model.

97
 98 At this stage many geologists have little more to work with than a hand lens and assay
 99 reports, so this early ore typing is often informal and simple. It may be as elementary as barren /
 100 low-grade / high-grade, plus a short identification of the one or two most common ore minerals.

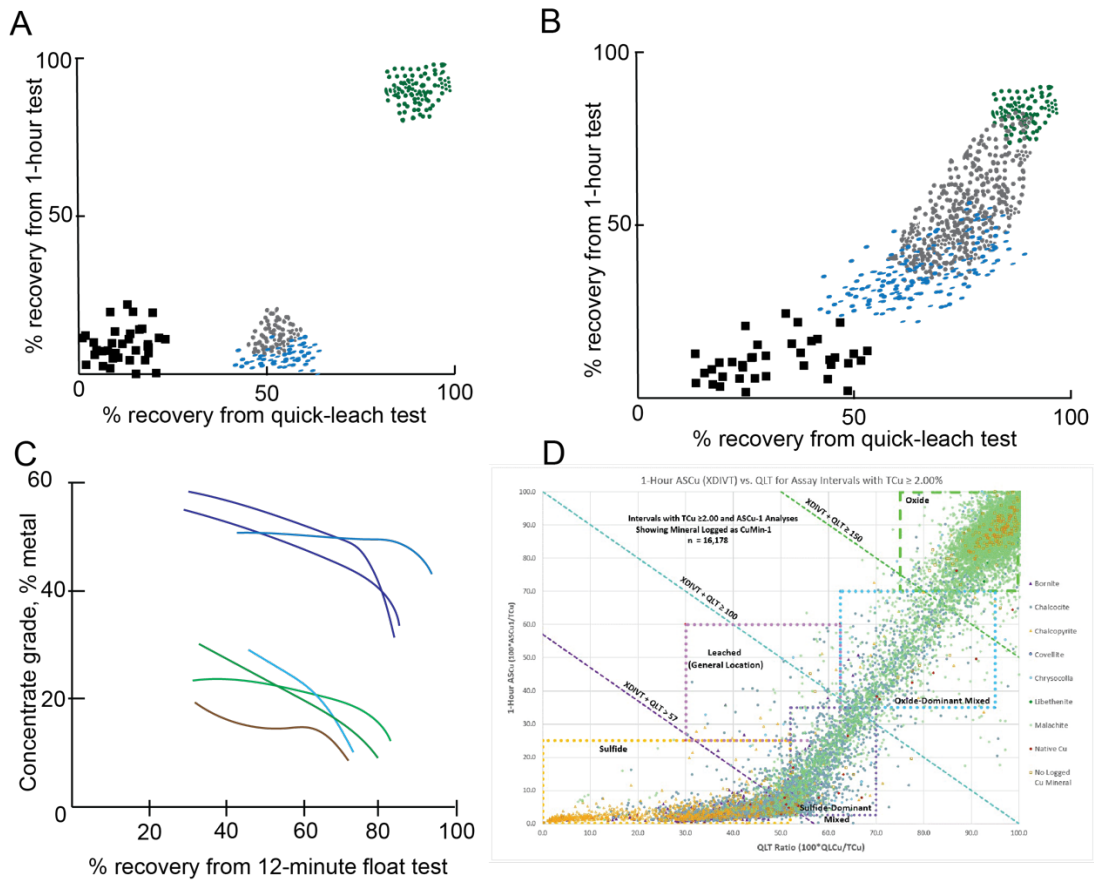
101 As exploration and development proceed, however, geologists start to break the rocks into more
102 detailed ore types as they drill out, delineate, and finally model the deposit (Hutson, this
103 volume). Ore typing at this stage remains primarily geological: grade, rock type, alteration
104 minerals, and dominant ore minerals make up the main criteria. This geological ore type is
105 usually entered in the drill core logs.

106 During this part of the process metallurgical data are primitive and partial. Results of leach
107 testing, flotation testing, grindability, etc. are incomplete and what does exist may not be
108 communicated to geologists. Data are rich but almost entirely geological. How the rocks will
109 behave during processing must be inferred from their mineralogy with no pretensions to
110 precision. As an example, a geologist modeling a deposit based on drill hole data might delineate
111 oxide, sulfide, and mixed zones in the orebodies on the understanding that they will be leached,
112 milled, and problematic respectively. Rocks with a high content of minerals obviously
113 deleterious to processing, such as swelling clays or carbonates (in acid leaching) might be
114 segregated into their own ore types or otherwise flagged. But verifying these intuitions with test
115 data and quantifying recoveries and other factors is not typical in the early, geological stage of
116 ore typing. The situation may be better for brownfields projects near existing mines, which can
117 use data from the current operation as at least a rudimentary guide to the probable behavior of
118 the new ores. (This is not always the case: new volumes of what look like existing ore types in
119 brownfields projects may behave differently from their equivalents at the active mine, sometimes
120 triggering a wholesale reexamination of ore typing at both.) Otherwise, attempts by geologists
121 and metallurgists to communicate about ore types in early-stage projects often lead to frustration
122 as one side needs to make plans with a precision that the other's data will not support. This gives

123 rise to situations like the old joke that a geologist says 2+2 equals “around 4, plus or minus”
124 while the engineer insists $2+2 = 4.00$.

125 As mine development proceeds, economic projections and mine planning demand a more
126 exact knowledge of how rocks will behave in processing and how much metal they will yield.
127 The ideal solution would be adjust geological ore typing to match the results of metallurgical
128 testing. A sampling study should have been carried out, samples collected in accordance with its
129 prescriptions and characterized, and then tested extensively under simulated process conditions.
130 This produces a large volume of quantitative and statistically representative data on rocks’
131 behavior during crushing, grinding, flotation, leaching, and downstream processes such as
132 roasting and smelting, as applicable to the metal and the mine. For best ore typing or for
133 geometallurgy, these data should be incorporated into the geological ore type model,
134 supplementing or occasionally replacing the geologist’s mineralogy-based inferences. In
135 practice, they are more often used to define expectations for recovery, reagent consumption, and
136 other important parameters for the already predetermined geological ore types.

137 When plotted with respect to the important metallurgical parameters (examples in Fig. 2),
138 test data will fall into tightly grouped clusters widely distinct from each other – if the
139 geometallurgist has rare good fortune. More often the data form a continuum which the poor sob
140 must somehow divide into discrete categories that simultaneously honor both geological and
141 metallurgical data, provide insight to the planners, minimize computational burden, remain
142 usable for samples and processes decades into the future, and pass managerial inspection. The
143 literature supplies no statistics on how many have gone insane during this quest for perfection.
144



145

146 Figure 2. Three hypothetical examples and one real example of ore typing. Each dot is a test
 147 datum and each color is a different dominant ore mineral. A: An unusually easy and rare ore
 148 typing case in which data fall neatly into three clusters, with different ore minerals but very little
 149 mixing. B: A more common ore typing in a deposit with a highly developed mixed zone. C: A
 150 relatively easy ore typing case using flotation data, with two neat clusters. D: An example from a
 151 copper mine, showing a continuum of test results divided into ore types by thresholds for QLT
 152 ratio and 1-hour acid-soluble leach test results (boxes) or by linear equations that incorporate
 153 both of those variables (diagonal lines); courtesy of R. North. Examples A, B, and C are
 154 fictitious.

155

156 *Assigning the “best” ore type*

157 Except in very clear-cut cases (Fig. 2a and 2c), there tends to be ambiguity about which
158 possible ore type best represents the characteristics of the material. Good ore typing will
159 minimize this, but the amount of overlap between ore types is seldom zero. In practice, mixing is
160 inevitable. There are almost always significant volumes of rock that fall near or on the
161 boundaries dividing one ore type from another, as shown in the more realistic Figure 2b and 2d.
162 Even if the separation between ranges of test results is clean and clear, however, it may not be
163 fully applicable to the mined units. Blasting, digging, and loading will cut across the volumes of
164 rocks that the test results represent. Thus the ore types determined and mapped onto the rock
165 must be further refined, with a “best” ore type selected and attached to the samples, the modeled
166 volumes of rock they represent, and the units that will be mined.

167 Procedures vary with the mine. One option is to develop a rule for borderline cases based on
168 which ore type has greater influence on processing behavior. For example, anything within 10%
169 of the boundary between sulfide-dominated mixed and oxide-dominated mixed ore types could
170 be automatically assigned to the sulfide-dominated mixed type. A second alternative is to bring
171 additional factors into consideration. If the boundary between sulfide-dominated mixed and
172 oxide-dominated mixed is determined by mineralogy and 1-hour leach test results, the results
173 from 6-hour leach testing may be examined to assign borderline cases to one or the other.

174 Some inconsistencies cannot be resolved in these ways. The mineralogy in the geologist’s log
175 or the QEMSCAN results may be inconsistent with the leach testing data, for instance. If re-logging
176 or re-testing is infeasible, the question becomes which data source is the most reliable. Common
177 practice is to weight metallurgical test results over geological and mineralogical data.

178

179 *Iterative assessment and revision of ore types*

180 Large mines may spend decades proceeding through different parts of the ore deposit. As
181 with short- and long-range planning, most such operations have a reconciliation process that
182 assesses how well the actual production from each ore type compares to predictions and whether
183 modifications are in order. If actual production is consistently over or under the prediction for
184 that ore type, and operational factors are not in the room when the blame is apportioned, the
185 usual result is scrutiny of the ore type. Consistent processing problems noticed during operations
186 may also trigger such a review apart from the reconciliation process.

187 This scrutiny can lead to modifications of some of the boundaries that divide ore types from
188 each other, or to the weights given to different metallurgical test types. For example, the 1-hour
189 acid-soluble Cu test may be found a more reliable predictor of recovery than QLT and be
190 weighted accordingly. Or metallurgists may discover that ores of type 4 that also contain $> 0.1\%$
191 As correlate with lower leaching recovery, and in that respect behave more like ore type 6. This
192 may lead to the expansion of ore type 6 or to the creation of ore type 4A. Alternatively, no test in
193 the existing battery may be able to distinguish the problem, in which case new options may be
194 tried. Ore typing is not a once-and-done process; instead, it is a long cycle of iteration and
195 improvement that may last as long as the mine does.

196

197 **Effective ore typing**

198 *The general idea*

199 Figure 2 shows easy and hard cases ore typing in mines. In the easy cases (Fig. 2a, 2c), a
200 bivariate plot of two metallurgical test results shows several clusters cleanly separated from each
201 other, corresponding to differences in the mineral logged as the dominant ore. In figure A, there
202 are three clusters based on the results of two different types of leach testing. In figure C, there are

203 two clusters based on flotation grade-recovery curves. Very few samples fall in between these
204 clusters and clear ore types therefore emerge. In these cases, the variables used in the plots will
205 have the heaviest weights for ore typing.

206 In the hard cases (2b, 2d), the ores are clearly mixed and the metallurgical test data points
207 form a continuum. At this point some arbitrary classifications become necessary. In the absence
208 of preexisting clusters in the geological or metallurgical data, or of overriding economic criteria,
209 the best procedure is to select the variables of greatest concern for the particular operation and
210 impose divisions in order from most to least important. For instance, quick-leach test recovery,
211 total metal content, geological log ore mineralogy, or flotation test results are likely to be used.
212 Some factors which are important but difficult to test may be out, since any test used for general
213 ore typing has to be applied to a huge number of samples over the course of development. This
214 makes parameters like Bond work index less useful for general ore typing despite their
215 operational importance.

216 Once the best variables for ore typing have been identified, the data are divided into ore types
217 by prescribing upper and lower boundaries for the most heavily weighted parameters, so that no
218 sample is outside of a box (Fig. 2). For example, a copper mine may define ore type 3 as any ore
219 with $TCu > 0.5\%$, QLT range 75-100%, and $ASCu$ range 65-100%. Alternatively, two variables
220 may be incorporated in an equation shown by the diagonal lines in Figure 2d. The exact
221 thresholds are set where the mine's economics dictate, typically at the break-even point between
222 different process options (e.g. dump leach vs. heap leach vs. flotation and smelting). The
223 principal is easily extended to incorporate multiple variables.

224 These first-order ore types typically relate to ore behavior in leaching, flotation, or roasting.
225 However, depending on the mine it may be necessary to create second-order or supplementary

226 ore types within the first-order categories (e.g. breaking ore type 5 up into 5A, 5B, and 5C). This
227 is particularly useful when some egregious rock, mineral, or alteration type causes consistent
228 serious problems in crushing and/or grinding. Some examples of this include rocks with a high
229 concentration of garnet, corundum, graphite, magnetite, or other minerals that have exceptionally
230 high A*b, Bond work index, or abrasion index in metallurgical testing. In these cases, rocks with
231 a primary designation of ore type 5 will be subjected to additional testing to determine the
232 subtype. This method allows the important comminution parameters to be identified where they
233 matter most, without having to go through expensive and time-consuming tests on a vast array of
234 rocks.

235

236 *Compositing intervals*

237 The metallurgical tests that produce ore typing parameters are usually conducted on
238 composited samples. Composites may consist of grouped samples over a regular interval (e.g.
239 every 10 meters of drill hole) irrespective of geological boundaries, or of samples grouped over a
240 regular interval for most of the distance with irregular lengths at start and end, reflecting
241 geological boundaries. The ore types constructed from these composites may thus reflect one
242 pure and unadulterated geological interval, or a mix of two to three different ones (Fig. 3).

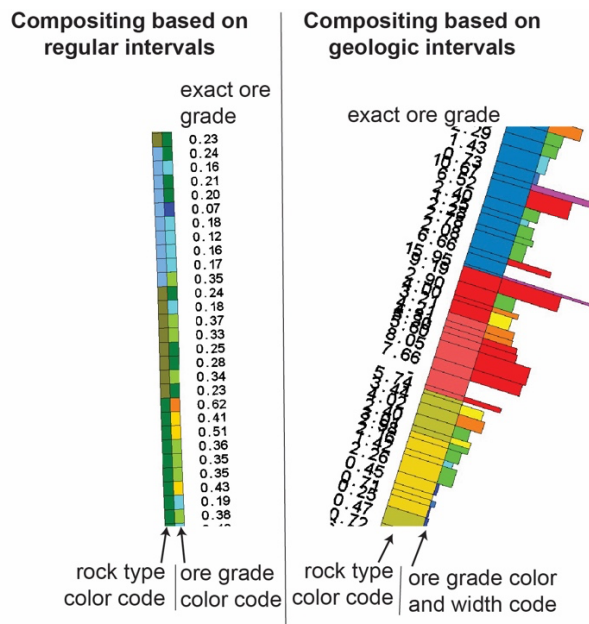
243 Geologists tend to prefer the second option (Fig. 3b), which offers the highest spatial
244 precision and greatest fidelity to the geological boundaries. This approach also minimizes the
245 chances of a single interval containing multiple ore types. Metallurgically, this reduces the
246 amount of slop or overlap between ore types and has the best probability of producing cleanly
247 clustered behavior as shown in Figure 2a and 2c. However, the uneven composite intervals can
248 create computational headaches in applying the ore type to the model. In general an approach

249 based on regular composite intervals is workable when the deposit is relatively homogeneous
 250 and ore grades and characteristics do not vary over short distances (e.g. the hypogene zone of a
 251 porphyry). In cases of high variability over short distances (e.g. stratabound or heavily faulted
 252 deposits) compositing based on geological intervals will yield the most accurate results.

253 Checking the semivariograms can illustrate which approach is better for a given deposit.

254 A third approach to compositing, based on (geo)metallurgical domains with known process
 255 behavior has also been suggested (e.g. Lotter et al., 2018). These can help subdivide ore types
 256 with relevant characteristics, for example bringing comminution-related parameters into play.
 257 However, this approach requires considerable advance knowledge of ore types and process
 258 mineralogy, and thus is likeliest to be deployed at existing mines in a limited capacity.

259



260

261 Figure 3. Drill hole profiles with rock type and assay codes based on regular (left) and geological
 262 (right) intervals. See text for discussion. Images courtesy of J. Waegli.

263

264 **Some common ore typing problems**

265 *Mixed ore zones*

266 Ore deposits with mixed zones are a particular ore typing headache. Mixed zones are
267 common among metals whose ores include both oxide (*sensu lato*) and sulfide minerals (copper,
268 cobalt, nickel, zinc, sometimes lead and antimony). Oxides are generally nearer the surface and
269 sulfides are below, but in between is an interval where supergene fluids have only partially
270 converted sulfides to oxides and both types of minerals are present. One may coat the other, with
271 the result that (for instance) an ore that is really sulfide-dominated is logged as mainly oxide.
272 The ratio between them varies wildly over short distances and can be difficult to assess in core
273 logging; QEMSCAN, which is useful for identifying what minerals are present, has too low
274 sampling statistics to be reliable for quantifying their proportions when they vary so much.
275 Depending on the reactivity of the sulfide minerals in leaching reagents, test results of both
276 leaching and flotation are likely to show partial recovery. Thus minerals like chalcocite, which
277 can be recovered by either leaching or flotation, particularly tend to smear test data out into a
278 continuum. Extensive chalcocite at one copper mine caused early attempts at designating ore
279 types using results from a 6-hour leaching test to fail. Over that length of time, chalcocite is
280 partially leachable under test conditions, meaning that ore types based on the 6-hour leaching test
281 reported some of the sulfide ores as oxides. The eventual, successful ore typing campaign instead
282 used the 1-hour leach test results to distinguish oxide-dominant and fully oxide ores from those
283 with substantial sulfide copper (R. North, unpub. data).

284

285 *Cryptic or variably metal-bearing ore minerals*

286 Mines that rely fully or partially on geological logging to designate ore types may encounter
287 problems with cryptic ore minerals. These can include ore minerals with a grain size too small to

288 detect with a hand lens, ore minerals coated by other minerals as described above, or “minerals”
289 that are really mineral groups with a range of possible compositions. The first of these is
290 common in precious metal mining, which may have to operate on ores with total concentrations
291 in the ppm range. The target metal, such as gold, may occur as inclusions or lattice substitutions
292 on what is otherwise not an ore mineral, commonly pyrite or arsenopyrite. In this case the ore
293 metal content can vary widely so that the abundance of the host mineral is no guide to the actual
294 grade. A rock with 1% pyrite may contain 50 g/t gold, or 5, and there is no way to tell without an
295 assay. Silver and platinum-group element mines have similar problems. The only solution is
296 typically to assay everything that looks even possibly ore-bearing and wait for the results.

297 Similar imprecision is a problem for base metal ore minerals that have a wide compositional
298 range. Sphalerite can range from pure ZnS to a ZnS-FeS mixture with nearly 50% Fe substituting
299 for Zn. A rock with 10% sphalerite can therefore have a Zn grade that varies by a factor of two.
300 The same is true of chalcocite, which is commonly given as Cu_2S but which is actually a mineral
301 group with compositions anywhere between CuS and Cu_2S . Every mineral on this spectrum is
302 recorded as chalcocite, but Cu contents cover a wide range. One study found that the zone
303 dubbed the “chalcocite blanket” at Morenci turned out, on detailed mineralogical examination, to
304 contain no actual chalcocite (Schumer et al., 2019). And metals hosted in phyllosilicate ores,
305 which almost invariably substitute for Mg, Fe, Al, or Si, almost always display a wide
306 compositional range. Recoveries can vary as much as metal content. Fortunately, in base metals,
307 compositional variability is less of a problem than in precious metals. Expert visual inspection
308 can usually at least tell whether the ore is high or low grade, and concentrations are high enough
309 for quick tools like the handheld XRF to detect and verify.

310

311 *Mixed blocks*

312 As with mixed ore types, boundaries between ore types will inevitably differ from boundaries
313 between blocks, resulting in some blocks containing two or more ore types. The obvious solution
314 is to tag the block with the majority ore type based on volume. While this solution is generally
315 adequate, it can lead to erroneous expectations in processes where combinations exhibit
316 nonlinear behavior. In such cases a fairly small minority of the mined unit can determine its
317 overall behavior. Comminution is a good example of this: if a block is only 25% garnet skarn ore
318 and 75% easily grindable altered porphyry, the overall grindability will be only slightly lower
319 than that of pure garnet skarn, since Bond work indices of mixed materials skew toward the least
320 grindable ingredient (Ipek et al., 2005). The block would probably be better assigned to the high-
321 garnet ore type than to the porphyry, at least as far as the mill is concerned.

322 In most mines such mixed blocks make up a small proportion of the deposit, so any problems
323 caused are relatively minor. If the nuisance is large enough to merit the work, the ore typologist
324 can develop an algorithm or system to assign blocks containing multiple ore types to the best
325 one. In the above example, if the mine has done extensive testing on mixtures, metallurgists may
326 assign any block with more than 15% overall garnet skarn to the garnet skarn ore type. If mixed
327 blocks represent a large fraction of the orebody, it may be because either the block dimensions or
328 the compositing intervals are unsuited to the geological situation, as discussed above.

329

330 *The scaling problem*

331 Laboratory testing, however good, cannot adequately represent phenomena that only show up
332 on the mine scale. Heap leaching is probably the most affected process route, since it involves
333 the largest amount of material being piled up in the same place without the continuous turnover

334 of milling processes. Even large column tests have limited ability to represent phenomena such
335 as compaction, heap-blinding, and fluid channeling which can seriously reduce recovery.

336 These issues usually escape notice during conventional ore typing. Hints of future problems
337 may be apparent early on, for instance if there are geological units or zones with particularly
338 high clay contents. The detection of swelling clays in any quantity should be a warning sign. But
339 the scale of the problem, and the potential need for a new ore type or subtype, may not be
340 apparent until the side of the leach heap blows out. The only real cure for it is prevention:
341 awareness and a sharp eye on the mineralogy can prevent ore types with too much swelling clay,
342 or high compaction factors, from being concentrated in the same area. After the problems have
343 developed, the only solutions are expensive interventions such as fracking the leach pad or re-
344 handling and moving large amounts of material.

345

346 *Changes over time*

347 At long-lived mines, the original ore type designations may not remain valid over the course
348 of operations. Whenever a process or operating conditions change substantially, it may be
349 necessary to adjust ore types. For instance, an ore that yielded low leach recovery at the original
350 conditions may start to leach better if the irrigation rate increases, agglomeration runs for longer,
351 and so forth. If the change in recovery is enough to affect the economic outcomes of leaching as
352 compared to flotation, it warrants reviewing and revising the mine's ore type designations even
353 though the rocks themselves have not changed.

354 At long-lived mines, the meaning of an ore type may also shift over time. As the mine moves
355 into different parts of the deposit, the ores' mineralogy, texture, and process behavior may
356 become subtly different from those the ore type originally described, without anyone noticing.

357 An ore type that meant one thing when mining started may mean something quite different 40 or
358 50 years later. Combined with likely changes in process operating conditions over that time, this
359 underlines the need for periodic updating of ore types.

360

361 **Conclusions**

362 The categorization of every rock in a mine into an ore type is a vital part of development and
363 extraction, but is usually fraught with difficulty. It typically begins in the exploration stage and is
364 based on ore mineralogy, grades, and other visible geological criteria. As development proceeds,
365 more metallurgical testing is performed and ore typing incorporates more quantitative variables
366 related to process outcomes. Which parameters are used to designate ore types will vary from
367 mine to mine, but the selection is generally based on which show the clearest useful distinctions
368 between rocks with different types of process behavior. In rare cases, metallurgical tests show
369 data points grouping into clear, distinctly separated clusters with respect to readily testable and
370 relevant process variables (leach test extraction, flotation grade-recovery curves, etc.). More
371 often metallurgical tests show a continuum of data points and ore types are artificially imposed
372 onto them, with considerable ambiguity and overlap no matter which parameters are used. Ore
373 typing at a first order is usually based on variables affecting overall process outcomes, such as
374 dominant ore minerals in the core logs, grade, and leach recovery. Secondary ore types or
375 subtypes may be needed for particular steps in the extraction process, for instance rocks with
376 exceptionally low grindability but no differences from the rest in overall recovery. These ore
377 types are determined from core logs and samples, coded onto assay intervals, and interpreted into
378 the geologic model. Eventually every block in the block model has a “best ore type” attribute
379 attached to it.

380 Common ore typing problems include the presence of a mixed zone where oxide and sulfide
381 ores coexist, a frequent feature of copper, cobalt, zinc, nickel, and a few other metals whose
382 mineralogy changes during supergene alteration. These exhibit variable, inconsistent, and hard-
383 to-quantify behavior in many processes and tend not to fall into distinct and easily typable
384 classes. Other problems include lack of alignment between block boundaries and ore type
385 boundaries, leading to some blocks containing multiple ore types; inability of lab-scale testing to
386 measure all relevant process parameters, particularly those that cause problems but only at large
387 scales; and poor communication between geologists and metallurgists. Even when ore types are
388 well-designed at the start of a project, they may not have been adjusted to changes in the
389 extractive process or subtle changes in the geologic characteristics. Continuous revisitation and
390 adjustment are needed to keep ore types up to date. Good ore typing sets the stage for optimal
391 process performance and maximum realistic extraction; bad ore typing can lead to chronic and
392 severe underperformance and failure to meet economic targets.

393

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397

398 **Conflict of interest statement**

399 On behalf of all authors, the corresponding author states that there is no conflict of interest.

400

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