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2 **Earth’s “missing” minerals**

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10 **ABSTRACT**

11 Recent studies of mineral diversity and distribution lead to the prediction of >1563 mineral
12 species on Earth today that have yet to be described—approximately one fourth of the 6394
13 estimated total mineralogical diversity. The distribution of these “missing” minerals is not
14 uniform with respect to their essential chemical elements. Of 15 geochemically diverse elements
15 (Al, B, C, Cr, Cu, Mg, Na, Ni, P, S, Si, Ta, Te, U, and V), we predict that approximately 25% of
16 the minerals of Al, B, C, Cr, P, Si, and Ta remain to be described—a percentage similar to that
17 predicted for all minerals. Almost 35% of the minerals of Na are predicted to be undiscovered, a
18 situation resulting from more than 50% of Na minerals being white, poorly crystallized, and/or
19 water soluble, and thus easily overlooked. In contrast, we predict that fewer than 20% of the
20 minerals of Cu, Mg, Ni, S, Te, U, and V remain to be discovered. In addition to the economic
21 value of most of these elements, their minerals tend to be brightly colored and/or well
22 crystallized, and thus likely to draw attention and interest. These disparities in percentages of
23 undiscovered minerals reflect not only natural processes, but also sociological factors in the
24 search, discovery, and description of mineral species.

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26 **Keywords:** Mineral diversity, nickel, sodium, tellurium, mineral ecology, mineral evolution,
27 chance versus necessity, philosophy of mineralogy, sociology of mineralogy

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INTRODUCTION

30 Earth's near-surface mineralogy has diversified significantly over 4.5 billion years as a
31 consequence of physical, chemical, and biological processes (Hazen et al. 2008, 2011, 2012;
32 Hazen and Ferry 2010). Hazen (2013) estimated that 420 mineral species may have been present
33 in the Hadean Eon, whereas as many as 1500 species arose from physical and chemical events
34 prior to 3 billion years ago. Biological processes, most notably near-surface environmental
35 changes following the Great Oxidation Event at 2.4 to 2.2 Ga and Phanerozoic biomineralization
36 subsequent to ~540 Ma, have led to numerous additional phases (Hazen et al. 2008, 2013a,
37 2013b; Sverjensky and Lee 2010; Dove 2010), including an estimated 70 percent of the ~5000
38 minerals approved by the International Mineralogical Association (rruff.info/ima; Downs 2006).

39 Earth's mineralogical diversity and distribution arise from both deterministic processes and
40 frozen accidents (Grew and Hazen 2014; Hazen et al. 2015). For example, chance and necessity
41 both play a role in the distribution of mineral species among the 72 essential mineral-forming
42 chemical elements. Previous authors have identified a correlation between the crustal abundance
43 of an element and the number of mineral species incorporating that element (Fig. 1; Yaroshevsky
44 and Bulakh 1994; Higgins and Smith 2010; Christy 2015; Hazen et al. 2015).

45 Deviations from this trend arise from several factors. On the one hand, fewer mineral species
46 than predicted by the general trend occur for rare elements that mimic more abundant elements
47 (*e.g.*, Ga for Al, Hf for Zr, and rare earth elements for Ce and Y). On the other hand,

48 significantly more mineral species tend to occur for elements with multiple oxidation states (*e.g.*,
49 Cu, Te, or U), unique coordination geometries (*i.e.*, elements with lone-pair electrons), and/or
50 multiple geochemical roles (*e.g.*, Cu forms chalcogenides, oxides, and halides).

51 In this contribution we examine another potential contribution in the scatter of data in Figure
52 1—the unequal distribution of Earth’s “missing” minerals among different elements. Our
53 statistical studies of 15 diverse mineral-forming chemical elements suggest that documentation
54 of Earth’s mineralogy is more complete for some elements than for others. This analysis not only
55 reveals a new factor in the study of “anomalous mineral diversity” in the Periodic Table (Christy
56 2015), but it also points to as yet rarely explored sociological influences on the scientific study of
57 mineral diversity and distribution—influences in addition to the problem of the characterization
58 of new mineral species (*e.g.*, Bulakh et al. 2003).

59

60 **Mineral Diversity-Distribution Relationships**

61 The relative roles of chance versus necessity are notably reflected in the distribution of rare
62 minerals—those known from only a few localities. More than half of all mineral species are
63 recorded from 5 or fewer localities, with 22% of species known from only 1 locality (data
64 recorded in mindat.org as of 1 February 2014). Hystad et al. (2015a) discovered that the
65 relationship between mineral diversity and distribution is analogous to the frequency distribution
66 of words in a book—*i.e.*, a few words such as “a”, “and”, and “the” are very common, but most
67 words are used infrequently. Idiosyncratic combinations of rare words and phrases can be used to
68 identify the genre and authorship of an unsigned text, and they usually conform to a Large
69 Number of Rare Events (LNRE) frequency distribution (Baayen 2001; Evert and Baron 2008).

70 Here we explore how LNRE models can also be exploited in mineralogy to estimate the

71 minimum abundances, as well as some chemical characteristics, of as-yet-undiscovered mineral
72 species. In this work we employ two types of Large Number of Rare Events models—both
73 Generalized Inverse Gauss-Poisson (GIGP) and finite Zipf-Mandelbrot (fZM) distribution
74 functions (Hystad et al. 2015a, 2015b; see Supplementary Materials). These frequency
75 distributions use an empirical 3-parameter fit to model the number of mineral species found at m
76 localities, typically for $1 \leq m \leq 15$. The GIGP model is the more robust formulation; it works
77 well for all minerals, as well as for the 15 subsets of minerals containing diverse elements. The
78 fZM model is more sensitive to scatter in mineral species-locality data; hence, we were unable to
79 fit the data for C, Cr, Na, and Si to fZM models. We employed the fZM model when possible,
80 because it facilitates calculation of individual probabilities in the population, which can be used
81 to run simulations of alternative “Earth-like” planets (Hystad et al. 2015b). By contrast, direct
82 calculation of probability distributions are not yet possible for GIGP models, though efforts are
83 now underway to solve this problem.

84 Our initial analysis considered 4831 Earth minerals from 135,415 localities with 652,856
85 individual mineral-locality data (Fig. 2a; Hazen et al. 2015; Hystad et al. 2015a). Large number
86 of rare events models are used to calculate “accumulation curve,” which document the rates of
87 discovery of new mineral species as more mineral species-locality data are recorded.
88 Accumulation curves extrapolate to the predicted total number of mineral species on Earth today
89 (Fig. 2b). These methods, which are widely employed in ecological studies of species diversity,
90 lead to the prediction of a minimum of 6394 minerals, implying that at least 1563 mineral
91 species exist on Earth today, but have yet to be documented. This prediction is a robust minimum
92 estimate, in spite of the many inaccuracies and incompleteness of the mindat.org crowd-sourced
93 data resource. Because the mindat resource constitutes such a large dataset, we suggest that

94 database errors will not introduce significant bias if used only for extrapolating large-scale
95 patterns—a conclusion reached by Adrain and Westrop (2000) for a comparable global database
96 of fossil genera “rife” with error. Our predicted numbers of missing species represent minimum
97 values because new search strategies (*e.g.*, field deployment of hand-held Raman spectrometers
98 or targeted field studies based on the findings reported herein) and analytical tools (*e.g.*,
99 transmission electron microscopic or confocal micro-Raman spectroscopic identification of
100 micro/nanophases) are continuously being introduced and thus expand the range of detectable
101 species.

102

103 **ELEMENTS DISPLAY DIFFERENT PERCENTAGES OF MISSING MINERALS**

104 Formalisms employed to estimate the total number of Earth’s missing minerals can also be
105 applied to subsets of the 652,856 species-locality data based on geographic locality, age of
106 formation, lithological context, chemistry, or other objective criteria. Here we employ LNRE
107 frequency models to analyze the numbers and percentages of missing minerals for 15 diverse
108 chemical elements (Goldschmidt 1937): Al, B, C, Cr, Cu, Mg, Na, Ni, P, S, Si, Ta, Te, U, and V.
109 Table 1 lists the total number of known minerals, predicted mineral diversity, and percent
110 missing minerals for each of these elements.

111 The 15 elements for which we have obtained LNRE frequency distributions vary in terms of
112 the percentages of their missing minerals. Seven elements—Al (27.1%), B (26.1%), C (26.5%),
113 Cr (22.3%), P (25.5%), Si (28.4%), and Ta (28.6%)—have percentages similar to that for all
114 minerals (24.4%). However, fewer than 20% of minerals are predicted to be missing for 7
115 elements—Cu (17.4%), Mg (18.4%), Ni (15.6%), S (17.8%), Te (9.9%), U (17.6%), and V
116 (19.6%). By contrast, 34.7% of Earth’s sodium minerals are predicted to be as yet undescribed.

117 Figures 2, 3, and 4 display frequency spectra in the form of bar plots (*a*) for m localities ($1 \leq$
118 $m \leq 15$), and mineral species accumulation functions (*b*), for all minerals (Fig. 2), nickel
119 minerals (Fig. 3), and sodium minerals (Fig. 4). These plots reveal important characteristics of
120 mineral diversity-distribution systematics. Of special importance in Figures 2*b*, 3*b*, and 4*b* are
121 ratios of minerals from 1 ($m = 1$) versus 2 ($m = 2$) localities, as indicated in curves labeled 1 and
122 2, respectively. Initially, the number of minerals known from only 1 locality rapidly outpaces
123 minerals known from exactly 2 localities. However, as the number of data increases, minerals
124 with $m = 1$ reach a maximum and then start to decrease, but those with $m = 2$ continue to
125 increase. Eventually, when most mineral species have been discovered, both the $m = 1$ and $m = 2$
126 curves decrease; ultimately, the number of minerals known from 2 localities surpasses the
127 number known from only 1 locality. Thus, sodium (Fig. 4), with the highest percentage of
128 missing minerals, also has the highest ratio of minerals with $m = 1$ (273 species) compared to m
129 $= 2$ (122 species; $273/122 = 2.24$). All minerals (Fig. 2) display an intermediate value ($1062/569$
130 $= 1.87$), whereas nickel (Fig. 3) has a smaller ratio ($30/25 = 1.20$), and tellurium (Table 1) has
131 the smallest ratio ($25/25 = 1.00$) and, accordingly, the smallest percentage of missing minerals
132 (9.9%). Thus, for any subset of minerals, the ratio of minerals with $m = 1$ versus $m = 2$ correlates
133 with the percentage of missing minerals.

134

135 **MINERAL SPECIMEN APPEARANCE INFLUENCES THE PERCENTAGE OF MISSING MINERALS**

136 The distinctive appearance of mineral specimens appears to be the most important factor in
137 the varied percentages of missing minerals (Table 1; Fig. 5). On the one hand, sodium has the
138 highest predicted percentage of missing minerals (34.7%), while it also has the lowest percentage
139 of minerals that are easy to detect in hand specimen. Based on a systematic survey of mineral

140 photographs on mindat.org, we find that 49.5% of sodium minerals are colorful and/or occur in
141 distinctive crystals, whereas more than half of Na species are white or grey in color and fine-
142 grained or poorly crystalized. In addition, with the exception of some salts, sodium minerals tend
143 not to be economically important and thus may receive less scrutiny than minerals of some other
144 elements. Furthermore, many Na mineral species are water soluble and therefore unstable and
145 ephemeral in most crustal environments.

146 By contrast, the minerals of Cu, Mg, Ni, S, Te, U, and V—all elements for which smaller than
147 average percentages of minerals are predicted to be missing—also tend to produce minerals with
148 distinctive color, luster, and/or crystal form that are easily recognized (and thus popular with
149 mineral collectors). Of the 15 elements studied, copper (68.5%), magnesium (68%), nickel
150 (72%), and uranium (76%) display the greatest percentages of distinctive specimens, while sulfur
151 (62.5%) and vanadium (61%) are closer to the average value for all minerals (63%). In addition,
152 6 of these elements (Cu, Ni, S, Te, U, and V) are concentrated in economically important
153 deposits that have thus been disproportionately studied.

154 The case of tellurium minerals is of special interest. Of the 72 mineral-forming elements Te,
155 with more than 10 times the number of species than might be predicted from tellurium's crustal
156 abundance alone, displays the greatest positive deviation from the general trends in Figures 1 and
157 5. The deviation in Figure 1 results, in part, from tellurium's multiple oxidation states and varied
158 crystal chemical roles (Christy 2015). An additional factor is that Te has the smallest predicted
159 percentage of missing minerals (9.9%) of the elements studied (16 of 178 predicted species
160 total). As a corollary, Te is also the only element studied for which the numbers of minerals
161 known from 1 and from 2 localities are equal. Tellurium is also an extreme outlier in Figure 5,
162 having far fewer predicted missing species than would be expected from the relatively low

163 percentage of easily recognized Te mineral species (51%). We suggest that an important
164 contributing factor to the relative completeness of Te mineralogy, as well as the low percentage
165 of species that are easily recognized in hand specimens, is the intense targeted study of Te
166 minerals by a few distinguished research teams, notably S.A. Williams (21 new species, 1974 to
167 1982), E.M. Spiridonov and coworkers (8 new species, 1978 to 1989), A.C. Roberts and
168 coworkers (14 new species, 1994 to 2010), and the ongoing research of A.R. Kampf, S.J. Mills,
169 J. Marty, and coworkers (13 new species, 2010 to present; *e.g.*, Housely et al. 2011, and
170 references therein). The effectiveness of their efforts in identifying microscopic phases in thin
171 section is reflected in the predicted relative completeness of Te mineral inventories, despite the
172 relatively low percentage of species easily recognized in hand specimen.

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IMPLICATIONS

175 Several factors influence the differing percentages of missing minerals for different chemical
176 elements. Physical and chemical characteristics play obvious roles. White and/or poorly
177 crystallized phases are more likely to be overlooked. In addition, elements that form highly
178 soluble salts, including halogens or alkali metals, or that form phases that are otherwise unstable
179 in a near-surface environment, are less likely to be found and catalogued.

180 Economic factors also play a significant role, as minerals of valuable elements have received
181 special scrutiny by mineralogists—intense study that must have biased the observed distribution.
182 Patterns of mineral discovery also reflect the sociology of mineralogy, particularly the
183 sensibilities of the mineral collecting community. We obtain mineral locality information from
184 the crowd-sourced database mindat.org. It is not surprising, therefore, that brightly colored,

185 lustrous, and/or morphologically distinct minerals are disproportionately represented owing to
186 observational bias.

187 The effects of different percentages of missing minerals for different elements would have a
188 modest but significant impact on the positions of points in Figure 1. If we considered all
189 minerals, including Earth's predicted missing minerals, for each element, then all points in
190 Figure 1 would shift upward. However, points for elements with relatively well-documented
191 minerals, including Cu, Mg, Ni, S, Te, U, and V, would shift less relative to the average, whereas
192 the point for underdescribed Na minerals would shift more.

193 This study illustrates the great promise of exploiting ever growing mineral data resources,
194 coupled with the application of powerful statistical methods. We anticipate that the discovery of
195 new minerals, which has traditionally been based on chance finds, can transformed to a predictive
196 science. To bring this opportunity into reality, we have commenced a series of contributions in
197 which we will identify likely compositions and localities of Earth's "missing" minerals.

198

199

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206

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- 262

263 **Table 1.** Numbers of known mineral species; predicted number of species; inferred number of
264 missing species; percentage of missing species; and percentage of species easily recognized in
265 hand specimens owing to color and/or crystal form (see text).

266

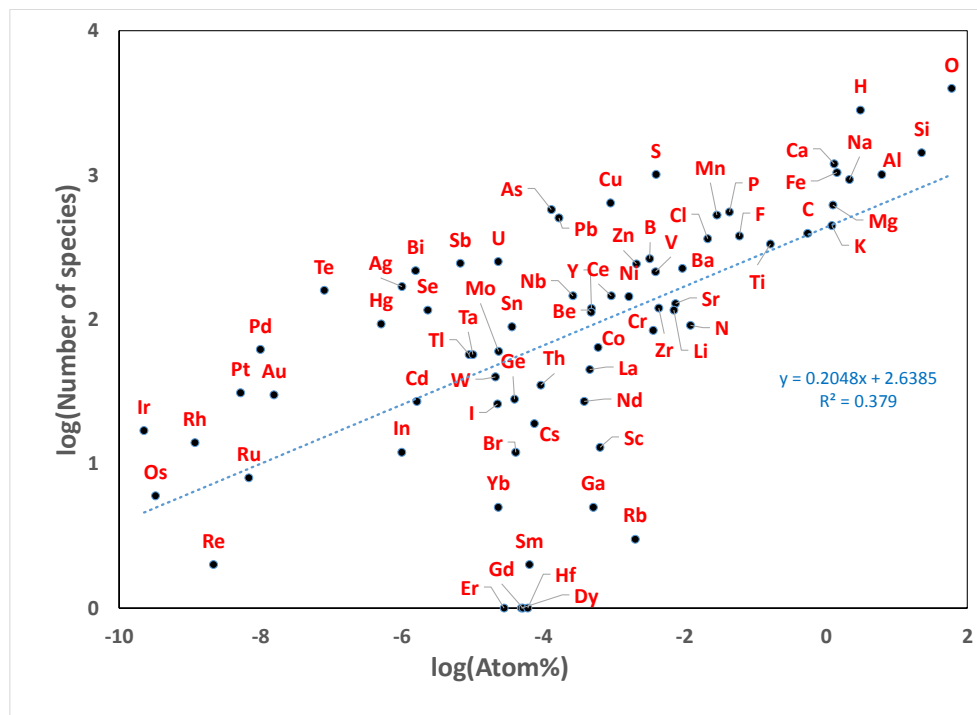
267	Element	# Known Species	# Predicted	# Missing	% Missing	% Easily Recognized
268	All species	4831	6394	1563	24.4	63
269	Al	1005	1378	373	27.1	65
270	B	269	364	95	26.1	62
271	C	403	548	145	26.5	62
272	Cr	94	121	27	22.3	56
273	Cu	658	797	139	17.4	68.5
274	Mg	628	770	142	18.4	68
275	Na	933	1429	496	34.7	49.5
276	Ni	151	179	28	15.6	72
277	P	579	777	198	25.5	62
278	S	1028	1250	222	17.8	62.5
279	Si	1436	2002	568	28.4	61.5
280	Ta	60	84	24	28.6	57
281	Te	162	178	16	9.9	51
282	U	252	306	54	17.6	76
283	V	218	271	53	19.6	61

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Figures and Captions

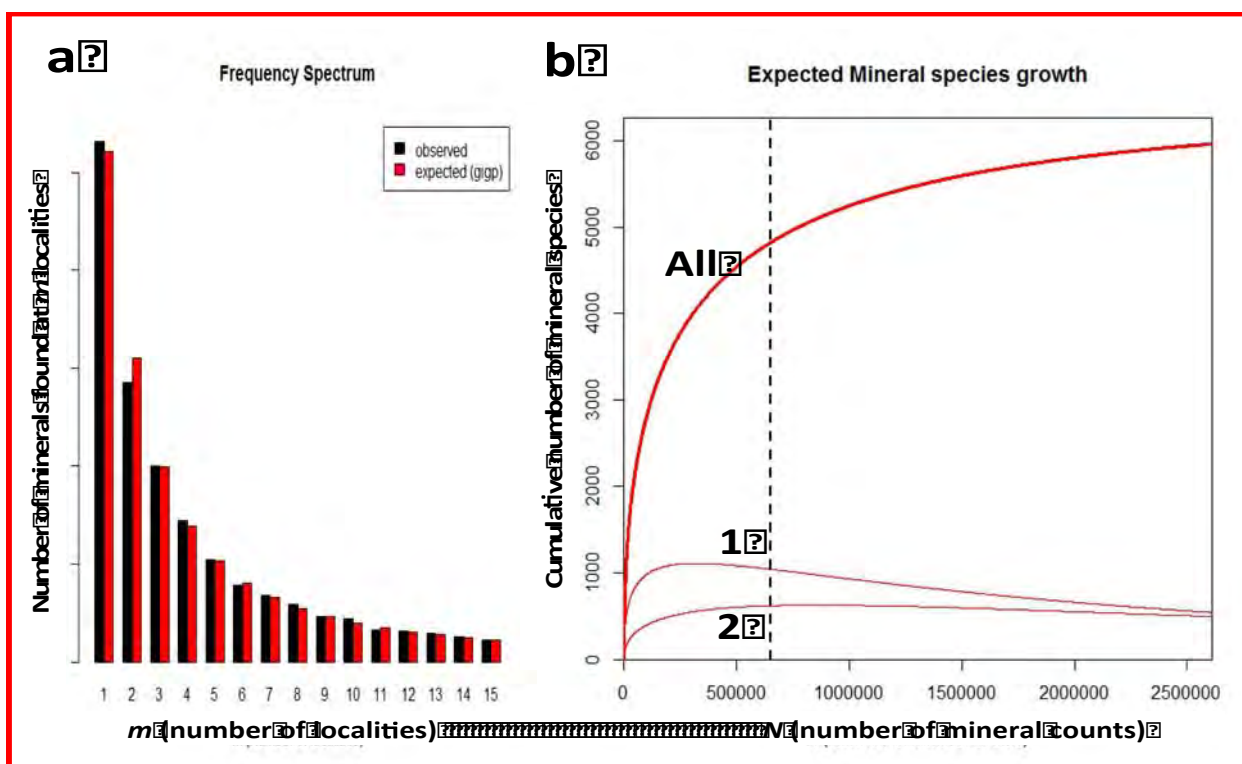
286 **Figure 1.** The number of known mineral species in Earth's upper crust is plotted versus crustal
287 abundance (in atom percent) for 72 essential mineral-forming elements (based on the data in
288 Hazen et al. 2015). Most elements plot close to the linear trend defined by all elements on this
289 log-log plot. Several rare elements that lie below the trend mimic more common elements (e.g.,
290 Ga for Al; Hf for Zr; REE for Ce or Y). Several elements that lie above the trend have multiple
291 oxidation states and/or varied crystal chemical roles. The percentage of as yet undescribed
292 minerals also plays a role in these deviations.



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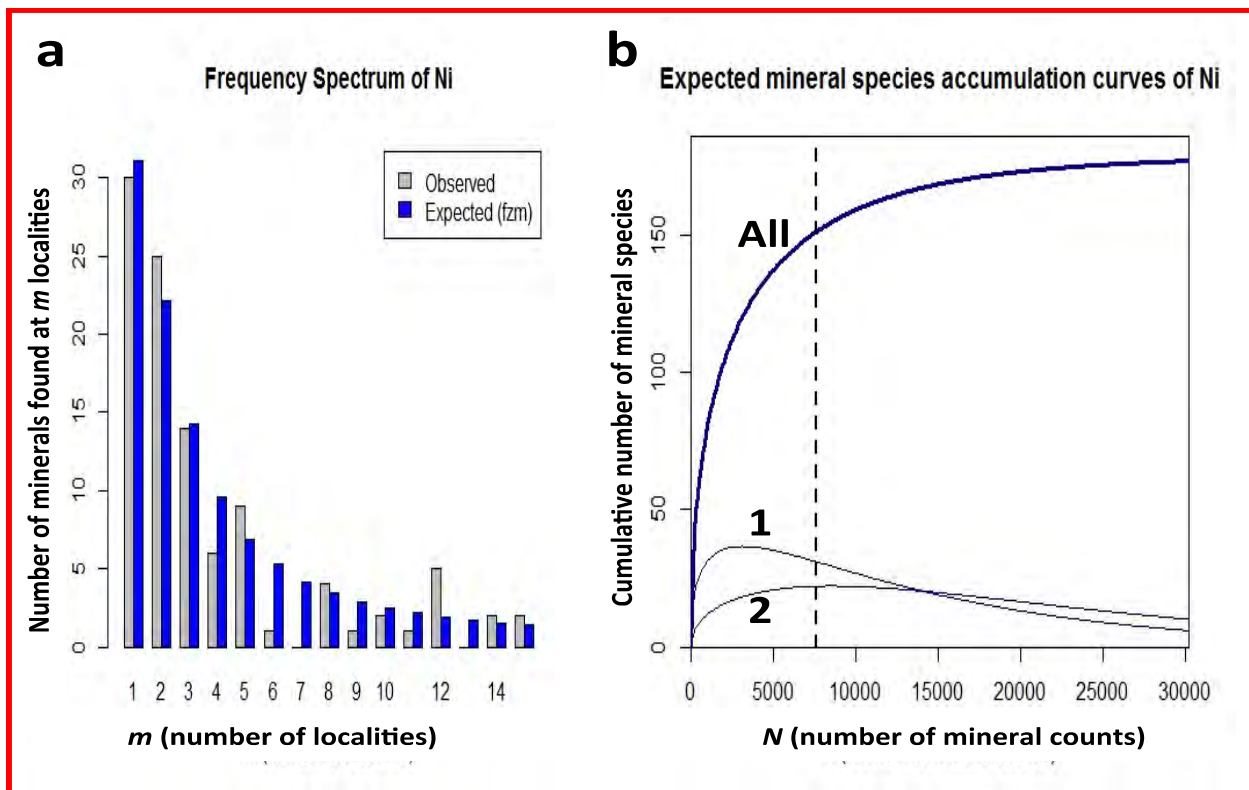
295 **Figure 2.** (a) Frequency spectrum analysis of 4831 Earth minerals, with 652,856 individual
296 mineral-locality data (from mindat.org as of February 2014), employed a Generalized Inverse
297 Gauss-Poisson (GIGP) function to model the number of mineral species for minerals found at
298 from 1 to 15 localities (after Hazen et al. 2015). (b) This model facilitates the prediction of the
299 mineral species accumulation curve (upper curve, “All”), which plots the number of expected
300 mineral species (y-axis) as additional mineral species/locality data (x-axis) are discovered. The
301 vertical dashed line indicates data recorded as of 1 February 2014 in mindat.org. The model also
302 predicts the varying numbers of mineral species known from exactly 1 locality (curve 1) or from
303 exactly 2 localities (curve 2). Note that the number of mineral species from only 1 locality is now
304 decreasing, whereas the number from 2 localities is now increasing, though it will eventually
305 decrease. We predict that the number of minerals known from 2 localities will surpass those from
306 1 locality when the number of species-locality data exceeds $\sim 3 \times 10^6$.



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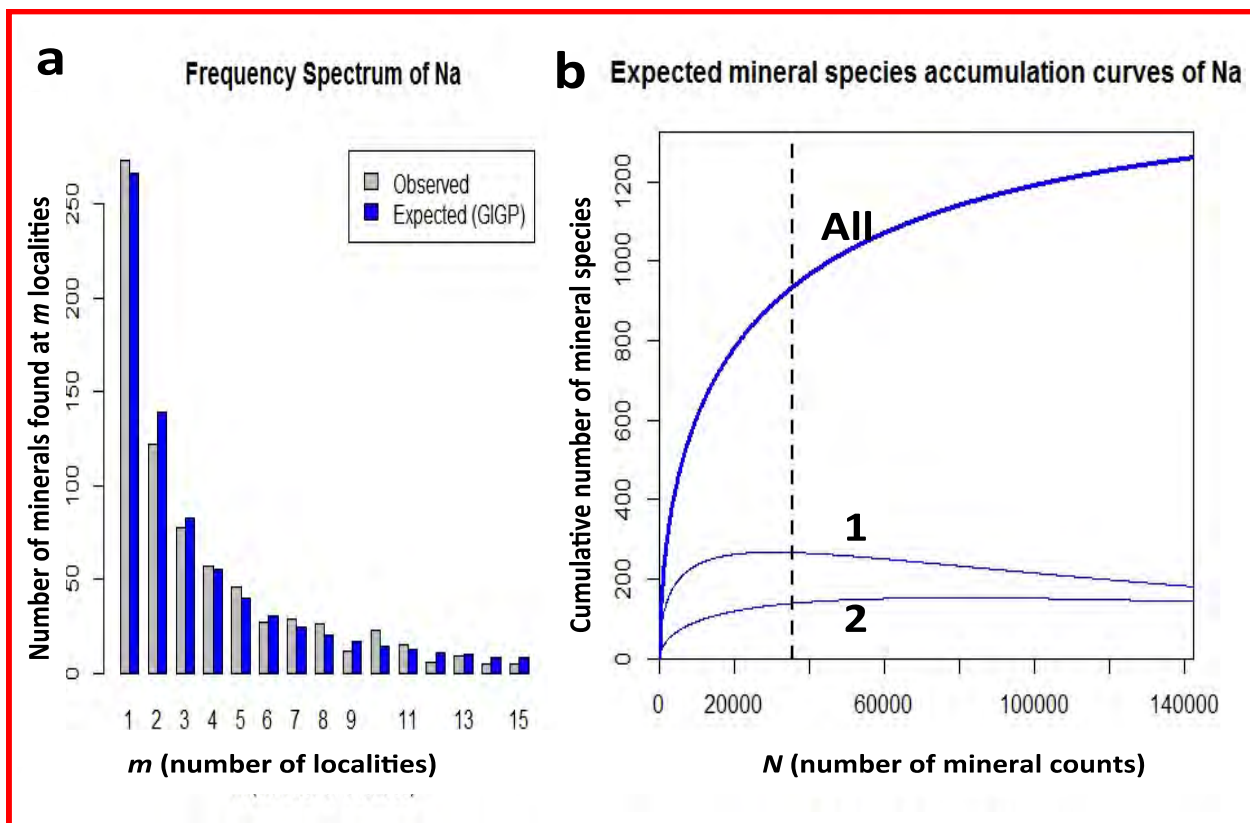
309 **Figure 3.** (a) Frequency spectrum analysis of 151 nickel minerals with 7567 individual mineral-
310 locality data (from mindat.org as of 1 February 2014). These data conform to a finite Zipf-
311 Mandelbrot (fZM) function that models the number of Ni mineral species found at from 1 to 15
312 localities. (b) Mineral species accumulation curve for nickel minerals: Note that the number of
313 mineral species from only 1 locality (curve 1) is now decreasing, whereas the number of
314 minerals from 2 localities (curve 2) is close to its maximum. We predict that the number of Ni
315 minerals known from 2 localities will surpass those from 1 locality when the number of species-
316 locality data exceeds 15,000.



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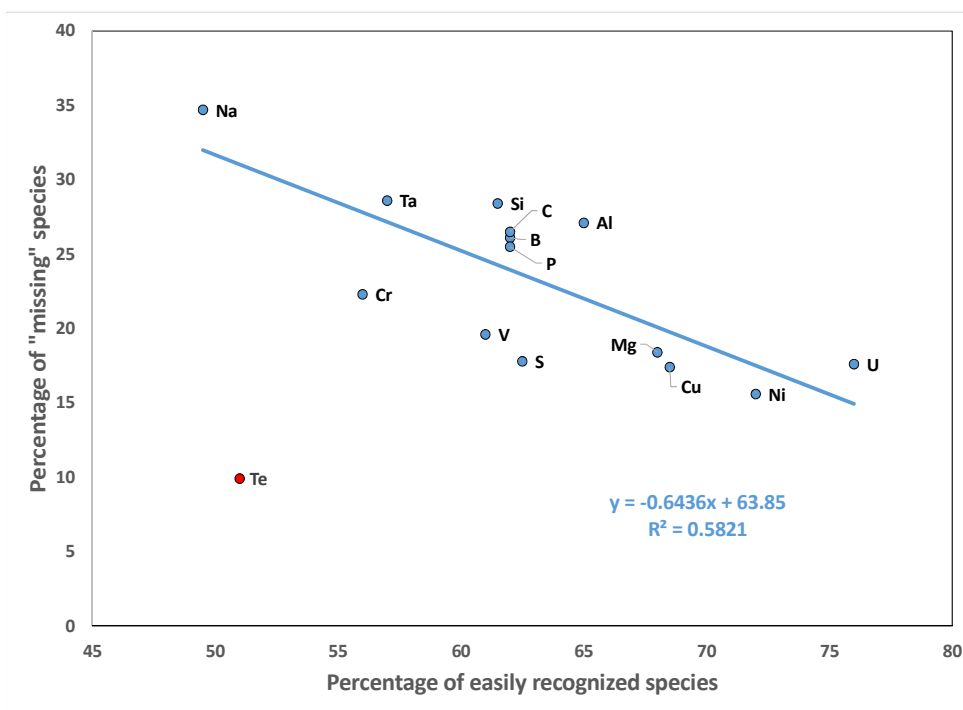
319 **Figure 4.** (a) Frequency spectrum analysis of 933 sodium minerals with 35,651 individual
320 mineral-locality data (from mindat.org as of 1 February 2014). These data conform to a finite
321 Zipf-Mandelbrot (fZM) function that models the number of Na mineral species found at from 1
322 to 15 localities. (b) Mineral species accumulation curve for sodium minerals: Note that the
323 number of mineral species from only 1 locality (curve 1) is more than twice that of the number of
324 minerals known from 2 localities (curve 2), in contrast to values in Figures 2 and 3.



325

326

327 **Figure 5.** The predicted percentage of missing minerals is inversely correlated with the observed
328 percent of specimens easily recognized in hand samples owing to their color and/or crystal form
329 (see text). The linear regression line excludes tellurium, which may be an outlier because of the
330 intense focus on discovering microscopic phases in thin section.



331