

Cobalt mineral ecology

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ABSTRACT

Minerals containing cobalt as an essential element display systematic trends in their diversity and distribution. We employ data for 66 approved Co mineral species (as tabulated by the official mineral list of the International Mineralogical Association, <http://rruff.info/ima>, as of 1 March 2016), representing 3554 mineral species-locality pairs (www.mindat.org and other sources, as of 1 March 2016). We find that cobalt-containing mineral species, for which 20% are known at only one locality and more than half are known from five or fewer localities, conform to a Large Number of Rare Events (LNRE) distribution. Our model predicts that at least 81 Co minerals exist in Earth's crust today, indicating that at least 15 species have yet to be discovered—a minimum estimate because it assumes that new minerals will be found only using the same methods as in the past. Numerous additional cobalt minerals likely await discovery using micro-analytical methods.

Primary Co minerals include 26 species, most of which are hydrothermally deposited chalcogenides. We identify 33 additional plausible as yet undiscovered primary cobalt chalcogenide minerals, including 28 phases with spinel, nickeline, pyrite, and marcasite structural topologies. All 40 secondary cobalt minerals are oxides, and 37 of these phases also incorporate hydrogen. We tabulate an additional 117 plausible secondary Co minerals that are related compositionally and/or structurally to known species. New cobalt minerals are likely to be discovered in specimens collected at the 10 most prolific Co localities, all of which are mining districts with hydrothermal Co mineralization and hosting at least 10 different primary and secondary Co species.

Keywords: Cobalt, mineral ecology, new minerals, statistical mineralogy, philosophy of mineralogy, rarity, accumulation curves, LNRE distributions

INTRODUCTION

Descriptive mineralogy has traditionally focused on new minerals as they are discovered by systematic surveys or chance finds. Predictions of the numbers, nature, and localities of Earth's as yet undiscovered crystalline phases have been less frequent. Applications of large mineralogical data resources (Hazen 2014; LaForte et al. 2015) coupled with statistical methods from ecology and lexicology (Baayen 2001; Evert and Baroni 2008) are now leading to predictions of how many minerals remain to be discovered in Earth's crust: Earth's "missing" minerals (Hystad et al. 2015a, 2015b; Hazen et al. 2015a, 2015b, 2016; Grew et al. 2016a).

Here we apply the methods of mineral ecology to the minerals of cobalt, a redox-sensitive first-row transition element that is of special interest because of its strategic importance (National Research Council 2008; Orcutt 2011), as well as its critical roles in biology (Young 1979; Kobayashi and Shimizu 1999). Cobalt is a relatively common minor element in the crust (Wedepohl 1995; Palme and Jones 2005), averaging ~20 ppm crustal abundance (Rudnick and Gao 2005), with an estimated 29 ppm in the bulk

continental crust and 10 ppm in the upper continental crust (Taylor and McLennan 1995), and 48 ppm in ocean basalt (Mielke 1979). Nevertheless, cobalt is an essential element in only 66 minerals, as recorded in <http://rruff.info/ima> as of 1 March 2016 (Downs 2006). rruff.info/ima is a web site created and maintained by the Outreach Committee of the International Mineralogical Association (IMA); it is the official IMA mineral list. The parsimony of cobalt minerals is a consequence of cobalt's charge and ionic radius mimicking that of the more common mineral-forming elements Fe, Ni, and Mg, making it easier for Co to incorporate as a minor element in abundant rock-forming minerals than to be isolated into its own species. Thus it is possible to complete a comprehensive survey of cobalt mineral species and their localities. A subsequent contribution will focus on the temporal distribution and tectonic settings of Co minerals.

THE MINERALS OF COBALT

The 66 minerals of cobalt (Table 1) all occur in crustal environments. We are not aware of any cobalt mineral reported exclusively from mantle rocks or from extraterrestrial environments; indeed the only reported extraterrestrial occurrences are three minerals in meteorites (Rubin 1997a, 1997b; Hazen et al. 2015a). Cobaltite

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TABLE 1. IMA recognized primary and secondary minerals of cobalt, with numbers of recorded occurrences in parentheses (see text), chemical formulas, paragenetic modes, and selected mineral localities (see Table 2 for key to localities; the type locality is designated by an underscored number)

No & Name (no. of localities) ^a	Formula	Paragenetic mode	Select localities (see Table 2 for key)
Primary Co minerals			
1 Allocasite (37)	CoAsS	Low- <i>T</i> hydrothermal	1,3,4,6,9,10,20,24,27,28,51
2 Bornhardite (3)	Co ²⁺ Co ₃ ³⁺ Se ₄	Hydrothermal	<u>31</u>
3 Carrolite (127)	CuCo ₂ S ₄	Hydrothermal vein deposits	1,5,7,10,12,13,17,18,26,28,32,35,42,47,50
4 Cattierite (31)	CoS ₂	Carbonate-hosted	2,5,8,12,13,17,18,19,20
5 Clinosafflorite (19)	CoAs ₂	Hydrothermal Co-Ni ore	1,3,6,8,13
6 Cobaltite (762)	CoAsS	High- <i>T</i> hydrothermal	1,2,3,4,6,7,8,10,12,13,15,16,17,18,19,20,21,22,23,25,26,27,28,30,31,34,35,40,41,43,44,45,46,47,50,52,56
7 Cobaltpentlandite (54)	Co ₉ S ₈	Hydrothermal	6,7,17,18,19,28,38,40,46
8 Costibite (15)	CoSbS	Hydrothermal	4,15,25
9 Ferroskutterudite (1)	(Fe,Co)As ₃	Hydrothermal	<u>41</u>
10 Freboldite (4)	CoSe	Hydrothermal; carbonate hosted	<u>31</u>
11 Glaucodot (108)	Co _{0.5} Fe _{0.5} AsS	High- <i>T</i> hydrothermal	1,2,4,10,16,25,27,28,42,51
12 Jaipurite (4)	CoS	Hydrothermal ore	<u>43</u>
13 Kieftite (3)	CoSb ₃	Sulfide skarn	<u>1,7</u>
14 Langsite (5)	CoAs	Hydrothermal zone	<u>6</u>
15 Linnaeite (181)	Co ₃ S ₄	Hydrothermal veins	1,3,5,7,10,13,14,15,17,18,19,22,25,27,32,35,40,41,50
16 Mattagamite (3)	CoTe ₂	Massive Te ore	19,44
17 Modderite (3)	CoAs	Heavy mineral concentrates	<u>45</u>
18 Oenite (1)	CoSbAs	Cu-Co skarns	<u>7</u>
19 Paracostibite (7)	CoSbS	Massive sulfide; hydrothermal	<u>47</u>
20 Safflorite (266)	CoAs ₂	Moderate- <i>T</i> hydrothermal	1,2,3,6,8,9,10,11,12,13,15,16,20,21,22,23,27,30,36,40,46,48,51
21 Siegenite (211)	CoNi ₂ S ₄	Hydrothermal sulfide vein	3,4,5,6,10,12,13,14,18,19,25,26,32
22 Skutterudite (474)	CoAs _{3-x}	Medium- to High- <i>T</i> veins	1,2,3,6,8,9,10,12,14,15,16,17,20,21,22,23,24,27,30,34,36,39,40,48,50,51
23 Trogtalite (8)	CoSe ₂	Hydrothermal ore	<u>31</u>
24 Tyrrellite (9)	(Co,Cu,Ni) ₃ Se ₄	Hydrothermal ore	<u>52</u>
25 Wairaurite (8)	CoFe	Serpentinization	<u>65</u>
26 Willyamite (16)	CoSbS	Carbonate-hosted veins	4,7,15,25
Secondary Co minerals			
27 Apowite (5)	CoSO ₄ ·4H ₂ O	Efflorescences with sulfides	11,29,46
28 Asbolane (122)	Mn ⁴⁺ (O,OH) ₂ ·(Co,Ni,Mg,Ca) _x (OH) _{2x} ·nH ₂ O	Weathering; ultramafic soils	1,2,3,4,5,9,10,11,12,16,21,23,24,26,36,39,42,48
29 Bieberite (53)	CoSO ₄ ·7H ₂ O	Oxidation of S-As ores	2,3,10,11,14,23,24,30,39
30 Bouazzerite (1)	Bi ₆ (Mg,Co) ₁₁ Fe ₁₄ (AsO ₄) ₁₈ (OH) ₄ ·86H ₂ O	Oxidation of ores	<u>1</u>
31 Burgessite (2)	Co ₂ (H ₂ O) ₄ (AsO ₄) ₂ ·H ₂ O	Secondary weathering zone	<u>6</u>
32 Cobaltarthurite (3)	CoFe ₂ ³⁺ (AsO ₄) ₂ (OH) ₂ ·4H ₂ O	Weathered zone	1,33
33 Cobaltaustinitite (5)	CaCoAsO ₄ (OH)	Oxidized zone of ores	1,2,11,34
34 Cobaltkieserite (2)	CoSO ₄ ·H ₂ O	Oxidized ore	3,35
35 Cobaltkoritnigite (17)	Co(AsO ₃ OH)·H ₂ O	Weathering of glaucodot	1,2,3,8,9,21,36
36 Cobaltlotharmeyerite (2)	CaCo ₂ (AsO ₄) ₂ ·2H ₂ O	Oxidized ore	<u>1,2</u>
37 Cobaltneustädteite (2)	Bi ₂ Fe ³⁺ (Co,Fe ³⁺)(AsO ₄) ₂ (O,OH) ₄	Oxidized ore	<u>2</u>
38 Cobaltoblodite (1)	Na ₂ Co(SO ₄) ₂ ·4H ₂ O	Oxidized ore	<u>39</u>
39 Cobaltomenite (6)	CoSe ⁴⁺ O ₃ ·2H ₂ O	Oxidized ore	5,37
40 Cobaltsumcorite (1)	PbCo ₂ (AsO ₄) ₂ ·2H ₂ O	Oxidized ore	<u>2</u>
41 Cobaltzippeite (2)	Co(UO ₂) ₂ (SO ₄)O ₂ ·3.5H ₂ O	Oxidized ore	3,39
42 Cochromite (3)	CoCr ₂ O ₄	Thermal metamorphism of chromite	<u>40</u>
43 Comblainite (4)	Ni ₆ Co ³⁺ CO ₃ (OH) ₁₆ ·4H ₂ O	Oxidized ore	5,31
44 Erythrite (742)	Co ₃ (AsO ₄) ₂ ·8H ₂ O	Oxidized ore	1,2,3,4,5,6,7,8,9,10,11,13,14,15,16,18,20,21,22,23,24,25,26,27,29,30,31,33,34,35,36,39,42,46,48,49,50,51
45 Hetrogenite (102)	Co ³⁺ O(OH)	Weathering	1,2,4,5,6,8,9,16,21,23,24,26,33,42
46 Hloušekite (1)	(Ni,Co)Cu ₄ (AsO ₄) ₂ (AsO ₃ OH) ₂	Oxidized ore	<u>1</u>
47 Jamborite (17)	Ni ²⁺ _{1-x} Co ³⁺ (OH) _{2-x} (SO ₄) _x ·nH ₂ O [<i>x</i> ≤ 1/2; <i>n</i> ≤ (1- <i>x</i>)]	Oxidized ore	<u>54</u>
48 Julienite (1)	Na ₂ Co(SCN) ₄ ·8H ₂ O	Incrustations on talc schist	<u>5</u>
49 Karpenkoite (1)	Co ₃ (V ₂ O ₇)(OH) ₂ ·2H ₂ O	Oxidized ore	<u>55</u>
50 Kolwezite (6)	CuCoCO ₃ (OH) ₂	Oxidized ore	<u>5</u>
51 Leverettite (1)	Cu ₃ CoCl ₂ (OH) ₆	Oxidized ore	<u>56</u>
52 Metakirchheimerite (2)	Co(UO ₂) ₂ (AsO ₄) ₂ ·8H ₂ O	Oxidized ore	3,9
53 Moorhouseite (12)	CoSO ₄ ·6H ₂ O	Effluoresces with S	1,2,3,9,11,14,29
54 Neustädteite (4)	Bi ₂ Fe ³⁺ (Fe ³⁺ ,Co ₂)(AsO ₄) ₂ (O,OH) ₄	Oxidized ore	2,22
55 Oursinite (1)	Co(UO ₂) ₂ (SiO ₃ OH) ₂ ·6H ₂ O	Secondary mineral	<u>5</u>
56 Pakhomovskiyite (1)	Co ₃ (PO ₄) ₂ ·8H ₂ O	Carbonatite alteration	<u>46</u>
57 Petewilliamsite (1)	(Ni,Co) ₃₀ (As ₂ O ₇) ₁₅	Oxidized ore	<u>48</u>
58 Pradetite (2)	CoCu ₄ (AsO ₄) ₂ (AsO ₃ OH) ₂ ·9H ₂ O	Oxidized ore	3,49
59 Rappoldite (1)	PbCo ₂ (AsO ₄) ₂ ·2H ₂ O	Oxidized ore	<u>2</u>
60 Roselite (15)	Ca ₂ Co(AsO ₄) ₂ ·2H ₂ O	Oxidized ore	1,2,4,8,9,34
61 Roselite-β (9)	Ca ₂ Co(AsO ₄) ₂ ·2H ₂ O	Oxidized ore	1,2,4,8
62 Schneebergite (3)	BiCo ₂ (AsO ₄) ₂ (OH)·H ₂ O	Oxidized ore	<u>2</u>
63 Smolyaninovite (11)	Co ₃ Fe ³⁺ (AsO ₄) ₄ ·11H ₂ O	Oxidized ore	1,2,4,24,34,35,51
64 Sphero-cobaltite (21) ^b	CoCO ₃	Carbonate alteration	1,2,5,11,14,22,26,54
65 Thérèse-manganite (2)	Co ₆ SO ₄ (OH) ₁₀ ·8H ₂ O	Oxidized ore	<u>49</u>
66 Wupatkiite (7)	CoAl ₂ (SO ₄) ₄ ·22H ₂ O	Oxidized zone	4,14

^a Locality data compiled from www.MinDat.org as of 1 March 2016.^b Sphero-cobaltite may also occur as a primary mineral.

(CoAsS) and safflorite (CoAs₂) have been reported only from the “fossil” Brunflo, Sweden meteorite, an altered H4-H5 chondrite, inferred to have fallen in calcareous mud at 460 to 470 Ma; the cobalt minerals formed by terrestrial alteration of pre-existing meteoritic minerals (Nyström and Wickman 1991). This leaves wairauite (CoFe) as the only cobalt mineral having a definitive meteoritic as well as terrestrial parentage. Hua et al. (1995) inferred that a single grain in the Ningqiang carbonaceous chondrite formed at low temperatures under relatively oxidizing conditions; wairauite was also reported from the CV3 chondrites Efremovka and Allende (Krot et al. 1999).

Terrestrial cobalt minerals can be divided into two groups. Primary phases (26 species) form principally by direct crystallization in vein deposits by hydrothermal processes. Several of these minerals, including cobaltite (CoAsS), linnaeite (Co₃S₄), safflorite (CoAs₂), and skutterudite (CoAs_{3-x}), are found at hundreds of localities (Table 2) and constitute major ores of cobalt. By contrast, most secondary cobalt minerals (40 species) result from alteration of other Co-bearing phases, principally by oxidative weathering, hydration, and/or other forms of alteration. Additional occurrences of secondary Co minerals arise through alteration of other minerals, most commonly Ni or Cu chalcogenides, that incorporate minor amounts of cobalt. Sphero-cobaltite (CoCO₃) is a special case, possibly occurring as both a primary phase crystallized from carbonate-rich solutions and as an alteration phase derived from primary Co minerals. However, most specimens occur as crystalline or botryoidal coatings on other phases, based on photos on www.mindat.org and other sources. Therefore, we include sphero-cobaltite in the list of secondary minerals.

Apart from cobalt itself, 25 of the 72 essential chemical elements found in minerals overall (<http://ruff.info/ima>; Hazen et al. 2015a) are also essential constituents of cobalt minerals. The most frequently encountered elements (Table 3) are oxygen (in 40 species), hydrogen (37), arsenic (29), and sulfur (22). Next in abundance are metals Fe (8), Ni (7), Cu (6), and Ca (5), while chalcogenides Se and Sb are both represented by 5 species. Forty-six of the mineral-forming elements occur in no known cobalt-bearing minerals; these elements include B, Ba, K, Ti, W, and Zn (all of which are represented in synthetic Co phases; Tables 4 and 5). Note that all but three of the 66 known Co-bearing minerals incorporate O, S, As, and/or Se [the exceptions being kiefite (CoSb₃), mattagamite (CoTe₂), and wairauite (CoFe)]. Fifteen Co minerals incorporate only two different chemical elements [Co plus S (4 species), As (5), Se (3), Sb (1), Te (1), and Fe (1)], whereas asbolane [Mn⁴⁺(O,OH)₂·(Co,Ni,Mg,Ca)_x(OH)_{2x}·nH₂O], bouazzerite [Bi₄(Mg,Co)₁₁Fe₁₄(AsO₄)₁₈O₁₂(OH)₄·86H₂O], and julienite [Na₂Co(SCN)₄·8H₂O] are the most chemically complex Co minerals, each with seven different essential elements. The average for 26 primary Co minerals is 2.5 essential elements per species, whereas the 40 secondary phases incorporate an average of 4.8 elements per mineral. The average number of essential elements in 66 cobalt minerals is 3.9 elements per species.

Coexisting elements in primary cobalt minerals differ markedly from those in secondary minerals in several ways. Oxygen is present in all 40 secondary Co minerals, but in none of the 26 primary Co species (with the possible exception of sphero-cobaltite, which may occasionally occur as a primary phase). All 37 known Co minerals with hydrogen are secondary; only cochromite

(CoCr₂O₄), petewilliamsite [(Ni,Co)₂(As₂O₇)], and sphero-cobaltite are anhydrous secondary minerals.

COBALT MINERAL ECOLOGY

Hystad et al. (2015a) reported that the relationship between the diversity and distribution of mineral species is similar to the frequency distribution of words in a book: typically a few words and phrases occur many times, but most words and phrases are used only once or twice. These rare words and phrases can thus be analyzed to identify the genre and authorship of an unsigned text, and they conform to a Large Number of Rare Event (LNRE) frequency distribution (Baayen 2001; Evert and Baroni 2008).

We modeled the frequency distribution of cobalt minerals based on the numbers of known localities for each of the 66 approved cobalt minerals. The easiest approach to estimating the number of localities for each species is to interrogate the crowd-sourced data resource www.mindat.org, which tabulates locality information for every mineral species. This approach was used in the initial mineral ecology studies (Hazen et al. 2015a 2015b; Hystad et al. 2015a 2015b). For cobalt minerals, we initially analyzed 3662 raw species-locality data from www.mindat.org (Supplemental¹ Table 1), with 13 species recorded at only one locality, an additional 8 species at exactly 2 localities, and 4 species at exactly 3 localities. By contrast, more than half of these species-locality data relate to 3 minerals—cobaltite (762 localities in www.mindat.org), erythrite (742), and skutterudite (474). The 13 most common cobalt minerals account for 92% of all species-locality data. This distribution of species among localities, with a few common species and many more rare ones, is typical of all minerals of all the elements, as well as subsets of minerals of each element (Hazen et al. 2015a, 2016; Hystad et al. 2015b; Grew et al. 2016b). These data fit to both a finite Zipf-Mandelbrot (fZM) and a Generalized Inverse Gauss-Poisson (GIGP) model (Hystad et al. 2015a; Supplemental¹ Text 1). The GIGP parameters for Co minerals ($\gamma = -0.2853056$; $B = 0.03610296$; $C = 0.2432292$; P -value = 0.81; Hystad et al. 2015a) facilitate modeling of the Co-mineral accumulation curve (Supplemental¹ Fig. 1), with a prediction of a total of at least 87 cobalt minerals. By this estimate, at least 21 Co-bearing minerals occur on Earth but have not yet been described.

Grew et al. (2016b) noted that uncritical use of locality data from www.mindat.org can lead to errors for two reasons. In some cases www.mindat.org does not list all known localities, leading to underestimates of the number of localities. Thus, for example, www.mindat.org lists only 2 localities (in Canada and Finland) for mattagamite (CoTe₂); however, a systematic search of Georef reveals another report of an Australian occurrence, for a corrected total of 3 localities. In other instances www.mindat.org lists too many localities because many of the distinct “localities” in www.mindat.org refer to specimens from different specific outcrops, veins, or quarries within a single ore body or mineralized zone, and thus should be treated as only 1 locality. Thus, the 9 www.mindat.org localities for cobaltlo-

¹Deposit item AM-17-15798, Supplemental Material. Deposit items are free to all readers and found on the MSA web site, via the specific issue’s Table of Contents (go to http://www.minsocam.org/msa/ammin/toc/2017/Jan2017_data/Jan2017_data.html).

TABLE 2. Mineral localities with the greatest diversity of cobalt minerals, number, and identity of Co minerals, their lithological settings, principal Co-mineral-forming elements, and deposit age

Locality	No. Co minerals	Lithological context (key elements)
1. Bou Azer District, Tazenakht, Ouarzazate Province, Morocco	22 (1,3,5,6,11,13,15,20,22 ; 28,30,32,33,35,36,44,45,53,60,61,63,64)	Veins in serpentinized ophiolite+diabase intrusions (Co,Ni,Cu,Ag with As>S)
2. Schneeberg District, Erzgebirge, Saxony, Germany	21 (4,6,20,22 ; 28,29,33,35,36,37,40,44,45,53,54,59,60,61,62,63,64)	Hydrothermal Ag-Bi-Co-Ni-U veins with As>S
3. Jáchymov District, Karlovy Vary, Region, Czech Republic	18 (1,5,6,11,15,20,21,22 ; 28,29,34,35,41,44,46,52,53,58)	Classic 5-element (Ag-Co-Ni-Bi-U) deposit; hydrothermal veins with S and As
4. Mount Isa, Cloncurry area, Queensland, Australia	14 (1,6,8,11,21,26 ; 28,44,45,60,61,63,64,66)	Fe oxide-Cu-Au deposit. (Co-Ni-As-S-Sb)
5. Katanga Copper Crescent, Katanga, Democratic Republic of Congo	13 (3,4,15,20 ; 28,39,43,44,45,48,50,55,64)	U with Co-Ni-Fe-S mineralization (656 Ma), followed by Co-Cu-S; no Ni-As (602 Ma) Carbonate hosted
6. Cobalt area, Timiskaming District, Ontario, Canada	12 (1,5,6,7,11,14,20,21,22 ; 31,44,45)	Hydrothermal Ag-Co-Ni-Cu-As-S quartz-calcite veins
7. Tunaberg, Nyköping, Södermanland, Sweden	11 (3,6,7,8,13,15,18,20,26 ; 43)	Co-Cu sulfides in a skarn zone
8. Ore dumps, Richelsdorf Smelter, Hesse, Germany	10 (4,5,6,20,22 ; 35,44,45,60,61)	Veins of Bi-Co-Ni-As-S (Cu-Pb-Zn)
9. Wittichen, Baden-Württemberg, Germany	10 (1,20,22 ; 28,35,44,45,52,53,60)	Ag-Bi-Co-Ni-U mineralization in granite
10. Siegerland, North Rhine-Westphalia, Germany	11 (1,3,6,11,15,20,21,22 ; 28,29,44)	F-Cu-Co-S-As mines
11. Lavrion District, Attiki Prefecture, Greece	9 (20 ; 27,28,29,33,44,50,53,64)	Cu-Zn-Pb-Ag ore related to emplacement of Miocene granodiorite into marbles and other Mesozoic metamorphic rocks
12. North Bohemia Uranium District, Liberec Region, Czech Republic	8 (3,4,6,14,20,21,22 ; 28)	Co-As-S
13. Nordmark District, Värmland, Sweden	8 (3,4,5,6,15,20,21 ; 44)	Metamorphosed Fe-Mn deposits; Pb-Mn-As-Sb; skarn mineralization; dolomite lens between potassic metarhyolites and basic rocks; Co incidental
14. Coconino County, Arizona, U.S.A.	8 (15,21,22 ; 29,44,53,64,66)	U mineralization
15. Broken Hill, Yancowinna Co., New South Wales, Australia	7 (6,8,15,20,22,26 ; 44)	Ag-Pb-Zn deposit; Co incidental
16. Port Radium District, Great Bear Lake, Northwest Territories, Canada	7 (6,11,20,22 ; 28,44,45)	U-Bi-Ag-Ni-Co with As-S
17. Shilu Mine, Changjiang County, Hainan Province, China	7 (3,4,6,7,15,21,22)	Fe oxide-Cu-Au deposit with Co, Ni, Ag, Pb, Zn
18. Zhongtiaoshan ore field, Yuanqu County, Yuncheng Prefecture, China	7 (3,4,6,7,15,21 ; 44)	Metasedimentary Cu deposit in black shale
19. Kuusamo, Northern Finland Region, Finland	7 (4,6,7,12,15,16,21)	Hosted by Paleoproterozoic Kuusamo Schist Au-Co-S with Ag-Cu-Mo-Ni-REE-U
20. Clara Mine, Wolfach, Baden-Württemberg, Germany	7 (1,4,6,20,22 ; 35,44)	Barite-fluorite veins with Cu-Ag-Pb hosted by gneiss and Triassic sandstone. Incidental Co-As-S.
21. Annaberg District, Erzgebirge, Saxony, Germany	7 (6,20,22 ; 28,35,44,45)	Vein deposits with Ag-Co-Ni-U. [Co-As] mineralization in Siluro-Devonian sediments
22. Marienberg District, Erzgebirge, Saxony, Germany	7 (6,15,20,22 ; 44,54,64)	Vein deposits of Fe-Ag-Sn-U-F. Co-Ni-S-As mineralization incidental
23. Kamsdorf, Saalfeld, Thuringia, Germany	7 (6,20,22 ; 28,29,44,45)	
24. Palhal Mine, Branca, Albergaria-a-Velha, Aveiro District, Portugal	7 (1,22 ; 28,29,44,45,63)	Cu-Ni mine
25. Hnúšťa, Rimavská Sobota County, Banská Bystrica Region, Slovakia	7 (3,8,11,15,21,26 ; 44)	

(Continued on next page)

tharmeyerite [CaCo₂(AsO₄)₂·2H₂O] in fact represent only two mineralization events—the Bou Azer District in Morocco, and the Schneeberg District of Saxony, Germany.

A relatively fast and straightforward approach to improved locality counts is to eliminate the geographically redundant www.mindat.org localities, while adding missing localities cited in the *Handbook of Mineralogy* but not in www.mindat.org. The resulting 3525 locality counts (Supplemental¹ Table 1) include 13 species from only one locality, an additional 10 species from exactly two localities, and six species from exactly three localities. These data fit to both fZM and GIGP models. The GIGP parameters ($\gamma = -0.6325573$; $B = 0.02307183$; $C = 2.189657$; P -value = 0.38; Hystad et al. 2015a) lead to a prediction of at least 80 cobalt minerals (see Supplemental¹ Fig. 2). This improved estimate of 14 “missing” Co-bearing minerals is significantly smaller than that obtained from the uncritical use of www.mindat.org data noted above.

Grew et al. (2016a) argue that the most valid approach to

determining the numbers of localities for each species is an exhaustive search of the primary literature for all but the most common species. (The exact locality counts for minerals known from more than 15 localities have little effect on LNRE models, which depend on the rarest species.) Therefore, we searched the primary literature for confirmation of every cobalt mineral locality for species with 50 or fewer localities reported on www.mindat.org—a task that required examination of approximately 1000 primary references. In the process we discovered 41 new localities distributed among 19 rare cobalt minerals, while eliminating 12 unconfirmed species-locality data. The resulting total of 3554 mineral species-locality data (Table 1) includes 13 species from only one locality, with an additional eight species from exactly two localities, and seven species from exactly three localities. These data fit to both fZM and GIGP models. The GIGP parameters ($\gamma = -0.4938359$; $B = 0.03418968$; $C = 0.701821$; P -value = 0.96; Hystad et al. 2015a) lead to a prediction of at least 81 cobalt minerals (Fig. 1). This model, and its estimate of 15

TABLE 2.—CONTINUED

Locality	No. Co minerals	Lithological context (key elements)
26. Cerro Minado Mines, Cuesta Alta, Almería, Andalusia, Spain	7 (3,6,21 ; 28,44,45,64)	
27. San Carlos Mine, San Juan de Plan, Huesca, Aragón, Spain	7 (1,6,11,15,20,22 ; 44)	
28. Banat Mountains, Caras-Severin Co, Romania	5 (1,3,6,7,11)	
29. Walton Barite Mine, Hants County, Nova Scotia, Canada	3 (27,44, <u>53</u>)	Barite, Pb-Zn-Cu; Co incidental
30. Bieber, Hesse, Germany	5 (6,20,22 ; 29,44)	
31. Lautenthal, Harz, Lower Saxony, Germany	6 (2,6,10,23 ; 43,44)	Veins in Ag-Pb-Zn-Cu-Ba in greywacke, associated with diabase intrusions. (Co-Ni-S-Se)
32. Sykesville, Carroll County, Maryland	3 (3,15,21)	
33. Dolores Prospect, Murcia, Spain	3 (<u>32</u> ,44,45)	
34. Olary Province, South Australia, Australia	6 (6,22 ; <u>33</u> ,44,60,63)	Calc-silicate hosted Cu-S/Co-As
35. Bästnas mines, Riddarhyttan, Västmanland, Sweden	6 (3,6,15 ; 34,44,63)	
36. Schwarzenberg District, Erzgebirge, Saxony, Germany	5 (20,22 ; 28,35,44)	
37. Cerro de Cacheuta, Mendoza, Argentina	1 (<u>39</u>)	Cu deposit in ultramafics; Co incidental
38. Varislahti deposit, South Karelia, Southern Finland, Finland	1 (<u>7</u>)	Cu-Ni-Co-Fe-S
39. White Canyon District, San Juan County, Utah, U.S.A.	6 (21 ; 28,29, <u>39</u> , <u>41</u> ,44)	
40. Barberton District, Mpumalanga Province, South Africa	6 (6,7,15,20,22 ; <u>42</u>)	
41. Noril'sk, Taimyr Peninsula, Eastern-Siberian Region, Russia	4 (6,9,15,20)	
42. Huasco, Atacama Region, Chile	6 (3,6,11 ; 28,44,45)	Cu with Co-U veins in diorite.
43. Jhunjhunu District, Rajasthan, India	2 (6,12)	Cu-Co-S veins
44. Mattagami, Nord-du-Québec, Québec, Canada	2 (6,22)	Zn-bearing massive sulfide
45. Witwatersrand field, Gauteng/Mpumalanga Provinces, South Africa	2 (6,17)	
46. Kovdor/Khibiny massifs, Kola Peninsula, Northern Region, Russia	6 (6,7,20 ; 27,44, <u>56</u>)	
47. Kenora District, Ontario, Canada	3 (3,6,19)	Cu-Pb-Zn with Co-Ni-S-As-Sb
48. Johanngeorgenstadt District, Erzgebirge, Saxony, Germany	5 (20,22 ; 28,44, <u>57</u>)	
49. Cap Garonne Mine, Var, Provence-Alpes-Côte d'Azur, France	4 (44, <u>53</u> , <u>58</u> , <u>65</u>)	Co minerals all secondary
50. Skutterud and nearby Mines, Modum, Buskerud, Norway	6 (3,6,11,15,22 ; 44)	Cu-Co-S vein deposits
51. Cobalt deposits, Tuva Republic, Eastern-Siberian Region, Russia	6 (1,11,20,22 ; 44, <u>63</u>)	
52. Beaverlodge Region, Saskatchewan, Canada	2 (6,24)	Co-Ni-Co-S-As-Se hydrothermal veins
53. Red Hill, Wairau Valley, South Island, New Zealand	1 (<u>25</u>)	Serpentinized zone
54. Northern Apennines, Emilia-Romagna, Italy	3 (15 ; <u>47</u> ,64)	
55. Yellow Cat District, Grand County, Utah, U.S.A.	1 (<u>49</u>)	
56. El Tamarugal Province, Tarapaca Region, Chile	2 (6 ; <u>51</u>)	

Notes: Listed are all localities with at least seven different Co mineral species, as well as additional localities that yielded the type specimen for each of the 66 known Co minerals (Table 1). The identification key to numbers for Co mineral species appears in Table 1; type minerals are designated by an underscored number. Numbers corresponding to the 26 primary Co minerals appear in boldface.

TABLE 3. Coexisting essential elements in cobalt minerals, including elements in the 26 primary vs. 40 secondary species

Element	No. of Co minerals	Primary	Secondary
O	40	0	40
H (All with O)	37	0	37
As	29	10	19
S	22	12	10
Fe	8	3	5
Ni	7	2	5
Cu	6	2	4
Ca	5	0	5
Se	5	4	1
Sb	5	5	0
C	4	0	4
Bi	4	0	4
Na	2	0	2
U	3	0	3
Mg	2	0	2
Pb	2	0	2
N	1	0	1
Al	1	0	1
Si	1	0	1
Cl	1	0	1
P	1	0	1
V	1	0	1
Cr	1	0	1
Mn	1	0	1
Te	1	1	0

Note: Numbers for 25 elements are based on mineral species and chemical formulas in <http://ruff.info/ima> as of 1 March 2016.

“missing” Co-bearing minerals, is nearly identical to that obtained by the simpler procedure of modifying www.mindat.org locality counts and adding additional localities from the *Handbook of Mineralogy*. However, it remains to be seen whether the simpler protocols are adequate for all mineral groups.

Note that our prediction of 15 Co minerals yet to be discovered is a minimum estimate because it assumes that cobalt minerals will continue to be discovered employing the same techniques as in the past. However, we suggest that a significant number of Co minerals have yet to be discovered by application of microanalytical techniques. Presently, an unusually high percentage of known Co minerals (55 of 66, or 83%) can be identified by their distinct color and/or morphology in hand specimen or with a hand lens. The relatively small percentage (16%) of Co minerals discovered by microanalytical techniques contrasts with minerals of many other elements, including Na and Te, for which as many as 50% of species have been discovered through microanalysis (Hazen et al. 2015b). Therefore, we suggest that dozens of additional Co minerals await discovery through micro-Raman spectroscopy, electron microprobe analysis, and/or electron microscopy—species that would not be reflected in our accumulation curve (Fig. 1b).

TABLE 4. Plausible as yet undescribed primary cobalt chalcogenide minerals, based on synthetic Co-bearing phases tabulated in the International Crystal Structure database that incorporate from 2–4 different chemical elements and possess structural topologies known from other primary Co minerals (Table 1)

Formula	Structure type	Related known minerals
Sulfides		
NiCo ₂ S ₄	Spinel	Co ₃ S ₄ (linnaeite); CuCo ₂ S ₄ (carrollite);
CoCr ₂ S ₄	Spinel	CoNi ₂ S ₄ (siegenite)
CoFeS ₂	Nickeline	CoS (jaipurite)
(CoCu)(S ₂) ₂	Pyrite	CoS ₂ (cattierite)
(CoNi)(S ₂) ₂	Pyrite	
(CoFe)(S ₂) ₂	Pyrite	
CoSeS	Pyrite	
Co ₃ FeS ₈	Pentlandite	Co ₉ S ₈ (cobaltpentlandite)
Arsenides		
CoAs ₂	Arsenopyrite	(Co,Fe)AsS (glaucodot)
CoAsSe	Pyrite	CoSe ₂ (trogtalite)
CoAs ₂	Marcasite	
CoAsSe	Marcasite	
Co ₂ AsSb	Nickeline	CoAs (langisite)
CoNiAs ₂	Nickeline	
Co _{0.5} Ni _{0.5} As ₂	Marcasite	
Co _{0.5} Fe _{0.5} As ₂	Marcasite	
Selenides		
Co ₃ Se ₈	Pentlandite	
CoSe ₂	Marcasite	
CoSbSe	Marcasite	
CoCr ₂ Se ₄	Spinel	Co ₃ Se ₄ (bornhardtite);
Co ₂ NiSe ₄	Spinel	(Co,Cu,Ni) ₃ Se ₄ (tyrrellite)
CoFe ₂ Se ₄	Wilkmanite	
CoNi(Se ₂) ₂	Pyrite	
CoNiSe ₂	Nickeline	CoSe (frieboldite)
Antimonides		
CoSb	Nickeline	
CoSb ₂	Marcasite	
Co _{0.5} Fe _{0.5} Sb ₂	Marcasite	
CoSbTe	Marcasite	
CoSb ₂	Monoclinic CoSb ₂	
Tellurides		
CoTe	Nickeline	
CoNiTe ₂	Nickeline	
CoTe ₂	Pyrite	
CoNi(Te ₂) ₂	Pyrite	

THE “MISSING” MINERALS OF COBALT

The 66 known minerals of cobalt represent a small fraction of the thousands of known inorganic Co compounds [Mellor 1935; International Crystal Structure Database (<http://icsd.fiz-karlsruhe.de>)]. Hazen et al. (2015a) suggested that every chemical element has the potential to form at least 1000 mineral species; however, relatively rare elements tend to form fewer mineral species because of the special geochemical conditions required to concentrate those elements (Christy 2015; Hazen et al. 2015b). Accordingly, Table 4 records 33 primary and Table 5 lists 117 secondary mineral-like synthetic Co compounds that have not been reported in nature, but which might occur in the inventory of as yet undiscovered cobalt minerals on Earth (or on other highly differentiated planets).

As a rare element that mimics the crystal chemistry of several other more common transition elements, including Fe, Ni, and Cu, most cobalt in Earth’s crust is probably distributed as a minor element in more common phases, most notably pyrite and other sulfides, but also oxides (notably spinel; Chauviré et al. 2015; Lenaz et al. 2015) and silicates, including pyroxene and olivine

(White et al. 1971; Morimoto et al. 1974; Mantovani et al. 2014). As a consequence, cobalt displays far fewer species than might be predicted from its crustal abundance (Christy 2015; Hazen et al. 2015). Only when Co is locally concentrated do phases with essential Co crystallize.

Synthetic cobalt phases point to plausible as yet undiscovered minerals. Table 4 lists 33 Co chalcogenides that possess the same structural topologies and incorporate the same elements as known minerals. These phases include 9 marcasite-type, 8 pyrite-type, 7 nickeline-type, and 4 spinel-type compounds—all of which are structures represented by common cobalt minerals. These synthetic phases also incorporate the same transition elements—Cr, Cu, Fe, and Ni—that are found in primary Co minerals.

Secondary cobalt minerals are compositionally more diverse, although all incorporate oxygen and all but two minerals incorporate hydrogen as an essential element. These compositional characteristics are reflected in our list of 117 plausible Co minerals that are known as synthetic compounds but have not yet been discovered in nature (Table 5). These cobalt compounds include CoO, well known as a synthetic phase with the rocksalt structure (e.g., Roth 1958; Sumino et al. 1980; Armentrout et al. 2013), as well as two other oxides (spinel-type Co₃O₄ and alumina-type Co₂O₃) and cobaltous hydroxide [Co²⁺(OH)₂] with the brucite structure. We also tabulate 11 plausible cobalt double oxides, all of which incorporate either Ca or a second transition element.

Only one cobalt silicate mineral has been approved by the IMA: oursinite [Co(UO₂)₂(SiO₃OH)₂·6H₂O], known from a single locality in the Democratic Republic of the Congo. A second potential cobalt silicate mineral is the Co-dominant analog of staurolite, “lusakite,” which was reported from near Lusaka, Zambia (Skerl et al. 1934); cobaltian staurolite has been described from Lusaka and Samos, Greece (Čech et al. 1981; Bringhurst and Griffen 1986; Taran et al. 2009). Phillips and Griffen (1986) synthesized the series staurolite-“lusakite” over the entire range of Co/(Co+Fe) from 0 to 1. In addition, several other synthetic cobalt silicates are known, notably cobaltian tourmaline (Taran et al. 1993; Setkova et al. 2009) and isomorphs of spinel, olivine, garnet, and pyroxene (e.g., Kohn and Eckart 1962; Geller 1967; White et al. 1971; Morimoto et al. 1974). Cobalt often substitutes as a trace element for Mg-Fe in natural analogues of these and other structures, but has not yet been found as the dominant cation. For example, from 1 to 7 wt% CoO has been found in högbomite, zincohögbomite, gahnite, ilmenite, magnetite, rhodonite, and Ni-dominant chlorite (Čech et al. 1976, 1981; Silayev and Yanulova 1993; Taran et al. 1989; Feenstra 1997; Feenstra et al. 2003).

Only one cobalt halide has been documented, the chloride leverettite [Cu₃CoCl₂(OH)₆], which is known from a single locality. Many additional synthetic fluorides and chlorides are known, most of which are hydrous compounds (Table 5).

Twenty-nine of the 40 known secondary cobalt minerals are sulfates, arsenates, or selenates. Table 5 records 38 additional examples known only as synthetic compounds. The majority of these synthetics, as with known minerals, are hydrous. All of these phases also incorporate other essential elements that occur in Co minerals, but we also list phases with potassium and barium—elements that are well documented in synthetic cobalt compounds but not yet known in natural examples.

TABLE 5. Plausible, as yet undescribed, secondary cobalt minerals, based on synthetic Co-bearing phases tabulated in the International Crystal Structure database that incorporate oxygen and from 1–5 additional chemical elements (Table 1)

Formula	Structure type
Co single oxides/Hydroxides	
CoO	Halite
CoO ₂	Cdl ₂
Co ₃ O ₄	Spinel
Co(OH) ₂	Brucite
Double oxides	
NiCo ₂ O ₄	Spinel
CoFe ₂ O ₄	Spinel
MnCo ₂ O ₄	Spinel
CoCu ₂ O ₃	
Ca ₂ CoO ₃	
CaCo ₂ O ₄	Harmunite
CoMnO ₃	
CoTiO ₃	Ilmenite
CoCrO ₄	CrVO ₄
CoMoO ₄	
CoWO ₄	
Silicates/Aluminates	
Co ₂ SiO ₄	Spinel
CoAl ₂ O ₄	Spinel
Co ₂ SiO ₃	Olivine
MgCoSiO ₄	Olivine
Ca ₂ Co(Si ₂ O ₇)	Akermanite
Co ₂ Al ₂ Si ₂ O ₁₂	Garnet
CaCo(Si ₂ O ₆)	Diopside
Na ₂ Co(Si ₄ O ₁₀)	Layer silicate
Fluorides	
CoF ₂	
CoF ₂ ·H ₂ O	
Co ₂ OF ₂ ·H ₂ O	
K ₂ CoF ₄	
KCoF ₃ ·H ₂ O	
NaCoF ₃ ·H ₂ O	
AlCoF ₃ ·7H ₂ O	
CoF ₃ ·nH ₂ O	
Chlorides	
CoCl ₂	
CoCl ₂ ·H ₂ O	
Co(OH)Cl	
Co ₂ (OH) ₃ Cl	
MgCoCl ₄ ·8H ₂ O	
Zn ₂ CoCl ₆ ·12H ₂ O	
ZnCoCl ₄ ·6H ₂ O	
Sulfates	
CoSO ₄	
Co ₃ (SO ₄) ₂ (OH) ₂ ·2H ₂ O	
Co ₂ (SO ₄) ₂ (OH) ₆ ·4H ₂ O	
NaCo(SO ₄)F	
NaCo ₂ (SO ₄) ₂ (H ₂ O)(OH)	
K ₂ Co ₂ (SO ₄) ₃	
K ₂ Co(SO ₄) ₂ ·2H ₂ O	
K ₂ Co(SO ₄) ₂ ·6H ₂ O	
CoNi(SO ₄) ₂ ·12H ₂ O	
Co(UO ₂)(SO ₄) ₂ ·5H ₂ O	
Arsenates	
Co ₂ (AsO ₄) ₂	
Co ₂ As ₂ O ₅	
Co ₂ As ₂ O ₇	Thortveitite
Co ₂ (AsO ₄)(OH)	Andalusite
Co ₂ (As ₂ O ₇)·2H ₂ O	
Co ₂ (AsO ₄)Cl	
BaCo ₂ (AsO ₄) ₂	
Co(UO ₂) ₂ (AsO ₄) ₂ ·12H ₂ O	

Two secondary hydrous carbonates have been described—the rare minerals complanite [Ni₆Co₃²⁺CO₃(OH)₁₆·4H₂O] and kolwezite [CuCoCO₃(OH)₂]. At least five additional mineral-like hydrous cobalt carbonates are known as synthetic compounds.

Only one cobalt phosphate is known in nature: pakhomovskiyite [Co₃(PO₄)₂·8H₂O], found only on the Kola Peninsula

TABLE 5.—CONTINUED

Formula	Structure type
Selenates	
Co(SeO ₄)·H ₂ O	
Co(SeO ₄)·5H ₂ O	
Co(SeO ₃)·H ₂ O	
Co(HSeO ₃) ₂ ·2H ₂ O	
Co(HSeO ₃) ₂ ·4H ₂ O	
Co ₃ (SeO ₃) ₃ ·H ₂ O	
Co ₃ (SeO ₃) ₄ Cl ₂	
Co(HSeO ₃)Cl·2H ₂ O	
Co(HSeO ₃)Cl·3H ₂ O	
Na ₂ Co(SeO ₄) ₂ ·2H ₂ O	Fairfieldite
K ₂ Co ₂ (SeO ₃) ₃	
K ₂ Co ₂ (SeO ₃) ₂ (OH)	
K ₂ Co ₂ (SeO ₃) ₃ ·2H ₂ O	
K ₂ Co(SeO ₄) ₂ ·2H ₂ O	
K ₂ Co(SeO ₄) ₂ ·6H ₂ O	
Ca ₃ Co(SeO ₃) ₄	
BaCo(SeO ₃) ₂	
BaCo ₂ (SeO ₃) ₃ ·3H ₂ O	
Co ₃ Fe ₂ (SeO ₃) ₆ ·2H ₂ O	
Co ₂ (UO ₂) ₃ (SeO ₄) ₅ ·16H ₂ O	
Carbonates	
Co ₂ (CO ₃)(OH) ₂	
K ₂ Co(CO ₃) ₂ (H ₂ O) ₄	
Na ₂ Co(CO ₃) ₂ (H ₂ O) ₄	
Ba ₂ Co(CO ₃) ₂ F ₂	
Na ₃ Co(CO ₃) ₂ Cl	
Phosphates	
CoPO ₄	
Co ₃ (PO ₄) ₂	Chopinite
Co ₃ (PO ₄) ₂ (H ₂ O)	
Co ₃ (PO ₄) ₂ (H ₂ O) ₆	
Co ₃ (HPO ₄) ₂ (OH) ₂	Lazulite
Co ₃ (PO ₄) ₂ (H ₂ O) ₄	
Co ₂ (PO ₄)(OH)	
Co ₂ (PO ₄) ₂ (OH) ₄	
Co ₃ (PO ₄) ₂ (OH) ₄	
Co(HPO ₄)(H ₂ O)	
Co(H ₂ PO ₄) ₂ (H ₂ O) ₂	
Co ₂ (PO ₄)Cl	
NaCo(PO ₄)	Olivine
NaCo ₄ (PO ₄) ₃	
NaCo ₃ (PO ₄) ₂ (OH)·H ₂ O	
Na ₂ Co(PO ₄)F	
KCo(PO ₄)	Andalusite
K ₂ Co(PO ₄) ₃	
KCo ₄ (PO ₄) ₃	
KCoAl(PO ₄) ₂	
KCo ₃ Fe(PO ₄) ₃	
KCo ₃ (PO ₄) ₂ ·H ₂ O	
KCo(PO ₄)·H ₂ O	
Mg ₃ Co ₃ (PO ₄) ₄	
BaCo ₂ (PO ₄) ₂	
Co(TiO) ₂ (PO ₄)	
Zn ₂ Co(PO ₄) ₂	
Zn ₃ Co ₃ (PO ₄) ₄	
ZnCo(PO ₄)(OH)	
CoZn ₂ (PO ₄) ₂ ·4H ₂ O	
CoFe(PO ₄)O	Sillimanite
Co ₂ Fe(PO ₄) ₂	
Co ₃ Cr ₄ (PO ₄) ₆	
FeCo(PO ₄)F	
Co ₃ (BO ₃)(PO ₄)	
Co(UO ₂) ₂ (PO ₄) ₂ ·10H ₂ O	

of Russia. Nevertheless, numerous synthetic Co phosphates have been described (36 of which appear in Table 5) and they point to the potential diversity if a deposit enriched in Co+P were to be discovered. In addition to 9 hydrous Co phosphates, compounds with Na, K, Mg, Ba, and several transition metals demonstrate the potential richness of these as yet undiscovered phases.

Several synthetic cobalt compounds incorporate elements that have not yet been found to coexist with Co in any mineral

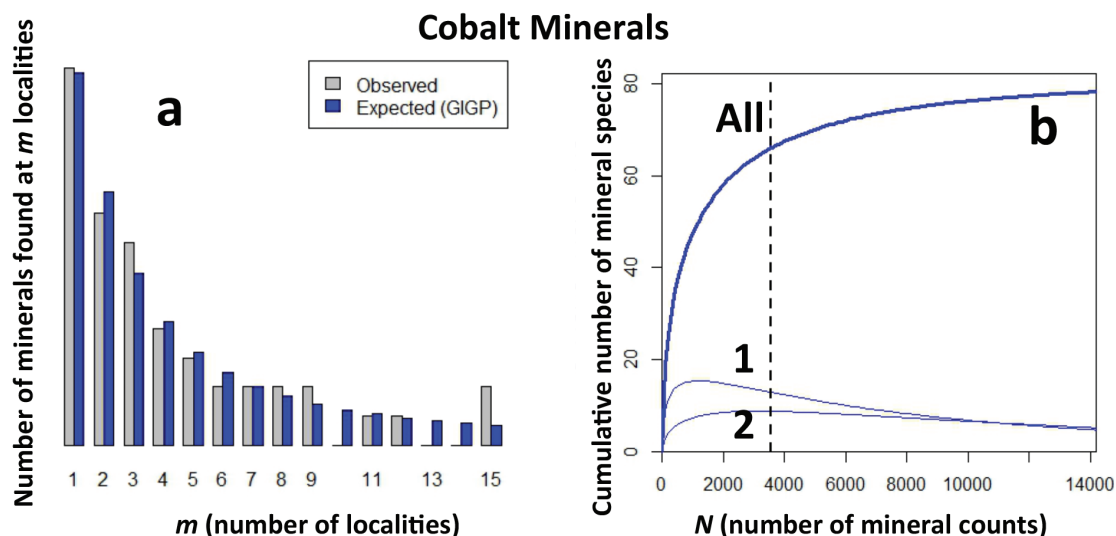


FIGURE 1. (a) Frequency spectrum analysis of 66 cobalt-bearing minerals, with 3554 individual mineral-locality data (from www.mindat.org as of 1 March 2016), employed a Generalized Inverse Gauss-Poisson (GIGP) function to model the number of mineral species for minerals found at exactly one to five localities (Hystad et al. 2015a). (b) This model facilitates the prediction of the mineral species accumulation curve (upper curve, “All”), which plots the number of expected Co mineral species (y -axis) as additional mineral species/locality data (x -axis) are discovered. The vertical dashed line indicates data recorded as of 1 March 2016 in www.mindat.org, as well as locality data from the *Handbook of Mineralogy* (Anthony et al. 2003) and systematic searching under each mineral name in GeoRef. The model also predicts the varying numbers of mineral species known from exactly one locality (curve 1) or from exactly two localities (curve 2). Note that the number of mineral species from only one locality is now decreasing, whereas the number from two localities is now increasing, but is almost at a maximum and will eventually decrease. We predict that the number of minerals known from two localities will surpass those from one locality when the number of species-locality data exceeds ~ 9000 . (Color online.)

species, but are plausible as candidates for as yet undiscovered natural phases. Most notably, these elements include potassium, which is known in dozens of synthetic cobalt halides, sulfates, selenates, carbonates, and phosphates. Other likely candidate elements in Co minerals include boron, barium, zinc, chlorine, and titanium, all of which are known in mineral-like synthetic Co compounds.

Note that we do not include Co^{4+} compounds, which have not yet been found in nature, but have been synthesized in various phases, including cobalt dioxide, CoO_2 , and various “percobaltites” such as Na_2CoO_3 , BaCo_2O_5 , and MgCoO_3 . The absence of natural Co^{4+} minerals is likely due to the fact that tetravalent cobalt requires redox conditions that are unlikely in any crustal environment, much less in Earth’s mantle.

This survey of plausible as yet undiscovered cobalt minerals points to strategies for the discovery of new Co phases. In particular, the 10 localities with 10 or more Co mineral species (Table 2) are especially rich in unusual species; they include type localities for 26 of 66 approved cobalt minerals. Close examinations of specimens from those localities, several of which are flooded or otherwise no longer accessible, are likely to yield additional cobalt minerals.

IMPLICATIONS: MINERAL ECOLOGY OF A TRACE ELEMENT

Previous studies in mineral ecology have focused on elements, including beryllium, boron, and carbon (Grew and Hazen 2014; Grew et al. 2016a; Hazen et al. 2016), that have unique crystal chemical characteristics and thus tend to concentrate in

their own minerals. Cobalt, by contrast, is the first element to be studied with this methodology that usually mimics more common elements—most notably magnesium, iron, and nickel—rather than form its own minerals. For example, ocean basalt, with total volume $\sim 3 \times 10^9 \text{ km}^3$ and density $\sim 3 \text{ g/cm}^3$ (and therefore total mass $\sim 9 \times 10^{24} \text{ gm}$), has an average Co content of 48 ppm, with up to 150 ppm in olivine (Herzberg et al. 2016). Ocean basalt thus holds $\sim 4 \times 10^{14}$ metric tons of cobalt—more than 50 000 000 times greater than the 2016 U.S. Geological Survey estimate of world cobalt ore reserves ($\sim 7.1 \times 10^6$ tons; <http://minerals.usgs.gov>). Even the most common primary Co minerals, such as cobaltite and skutterudite, are volumetrically insignificant by comparison. One might expect, therefore, that cobalt minerals display a different frequency distribution than minerals of more common elements, or of rare elements that are not readily incorporated as minor constituents of common rock-forming minerals.

Our results suggest that, on the contrary, the minerals of cobalt conform to a robust LNRE distribution that facilitates predictions of the numbers of as yet undiscovered Co mineral species, just as an LNRE distribution does for all minerals in Earth’s crust (Hazen et al. 2015a). We conclude that other subsets of minerals grouped by both major and minor elements could also conform to a LNRE distribution: the viability of LNRE modeling for boron minerals is currently under study (Grew et al. 2016a).

More general questions concern the underlying reasons for this fascinating statistical feature of minerals on Earth, and whether similar distributions occur on other worlds. In particular, the majority of rare cobalt minerals are secondary phases that arise from near-surface oxidation; these minerals are thus indirect

consequences of biological processes. Studies in progress will explore whether the observed LNRE distributions of Earth's minerals are uniquely a consequence of rare biologically mediated species and, consequently, if LNRE distributions are an unambiguous mineralogical signature of life on Earth-like planets.

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