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2   # Cobalt Mineral Ecology

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13   **ABSTRACT**

14   Minerals containing cobalt as an essential element display systematic trends in their diversity

15   and distribution. We employ data for 66 approved Co mineral species (as tabulated by the

16   official mineral list of the International Mineralogical Association, rruff.info/ima, as of 1 March

17   2016), representing 3554 mineral species-locality pairs (mindat.org and other sources, as of 1

18   March 2016). We find that cobalt-containing mineral species, for which 20% are known at only

19   one locality and more than half are known from 5 or fewer localities, conform to a Large

20   Number of Rare Events (LNRE) distribution. Our model predicts that at least 81 Co minerals

21   exist in Earth's crust today, indicating that at least 15 species have yet to be discovered—a

22   minimum estimate because it assumes that new minerals will be found only using the same

23   methods as in the past. Numerous additional cobalt minerals likely await discovery using micro-

24   analytical methods.

25   Primary Co minerals include 26 species, most of which are hydrothermally deposited

26   chalcogenides. We identify 33 additional plausible as yet undiscovered primary cobalt

27   chalcogenide minerals, including 28 phases with spinel, nickeline, pyrite, and marcasite

28   structural topologies. All 40 secondary cobalt minerals are oxides, and 37 of these phases also

29   incorporate hydrogen. We tabulate an additional 117 plausible secondary Co minerals that are

30   related compositionally and/or structurally to known species. New cobalt minerals are likely to

31   be discovered in specimens collected at the 10 most prolific Co localities, all of which are

32   mining districts with hydrothermal Co mineralization and at least 10 different primary and

33   secondary Co species.

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35   **Keywords:** cobalt, mineral ecology, new minerals, statistical mineralogy, philosophy of

36   mineralogy, rarity, accumulation curves, LNRE distributions

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INTRODUCTION

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41   Descriptive mineralogy has traditionally focused on new minerals as they are discovered by

42   systematic surveys or chance finds. Predictions of the numbers, nature, and localities of Earth's

43   as yet undiscovered crystalline phases have been less frequent. Applications of large

44   mineralogical data resources (Hazen 2014; LaFuente et al. 2015) coupled with statistical

45   methods from ecology and lexicology (Baayen 2001; Evert and Baroni 2008) are now leading to

46   predictions of how many minerals remain to be discovered in Earth's crust: Earth's "missing"

47   minerals (Hystad et al. 2015a, 2015b; Hazen et al. 2015a, 2015b, 2016; Grew et al. 2016a).

48   Here we apply the methods of mineral ecology to the minerals of cobalt, a redox-sensitive

49   first-row transition element that is of special interest because of its strategic importance

50   (National Research Council 2008; Orcutt 2011), as well as its critical roles in biology (Young

51   1979; Kobayashi and Shimizu 1999). Cobalt is a relatively common minor element in the crust

52   (Wedepohl 1995; Palme and Jones 2005), averaging ~20 ppm crustal abundance (Rudnick and

53   Gao 2005), with an estimated 29 ppm in the bulk continental crust and 10 ppm in the upper

54   continental crust (McLennan and Taylor 1999), and 48 ppm in ocean basalt (Mielke 1979).

55   Nevertheless, cobalt is an essential element in only 66 minerals, as recorded in rruff.info/ima as

56   of 1 March 2016 (Downs 2006). Rruff.info/ima is a website created and maintained by the

57   Outreach Committee of the International Mineralogical Association (IMA); it is the official IMA

58   mineral list. The parsimony of cobalt minerals is a consequence of cobalt's charge and ionic

59   radius mimicking that of the more common mineral-forming elements Fe, Ni, and Mg, making it

60   easier for Co to incorporate as a minor element in abundant rock-forming minerals than to be

61   isolated into its own species. Thus it is possible to complete a comprehensive survey of cobalt

62   mineral species and their localities. A subsequent contribution will focus on the temporal

63   distribution and tectonic settings of Co minerals.

64

65   **THE MINERALS OF COBALT**

66   The 66 minerals of cobalt (Table 1) all occur in crustal environments. We are not aware of

67   any cobalt mineral reported exclusively from mantle rocks or from extraterrestrial environments;

68   indeed the only reported extraterrestrial occurrences are three minerals in meteorites (Rubin

69   (1997a, b; Hazen et al. 2015a). Cobaltite (CoAsS) and safflorite (CoAs$_2$) have been reported only

70   from the "fossil" Brunflo, Sweden meteorite, an altered H4-H5 chondrite, inferred to have fallen

71   in calcareous mud at 460 to 470 Ma; the cobalt minerals formed by terrestrial alteration of pre-

72   existing meteoritic minerals (Nyström and Wickman 1991). This leaves wairauite (CoFe) as the

73   only cobalt mineral having a definitive meteoritic as well as terrestrial parentage. Hua et al.

74   (1995) inferred that a single grain in the Ningqiang carbonaceous chondrite formed at low

75   temperatures under relatively oxidizing conditions; wairauite was also reported from the CV3

76   chondrites Efremovka and Allende (Krot et al. 1999).

77   Terrestrial cobalt minerals can be divided into two groups. Primary phases (26 species) form

78   principally by direct crystallization in vein deposits by hydrothermal processes. Several of these

79   minerals, including cobaltite (CoAsS), linnaeite (Co$_3$S$_4$), safflorite (CoAs$_2$), and skutterudite

80   (CoAs$_{3-x}$), are found at hundreds of localities (Table 2) and constitute major ores of cobalt. By

81   contrast, most secondary cobalt minerals (40 species) result from alteration of other Co-bearing

82   phases, principally by oxidative weathering, hydration, and/or other forms of alteration.

83   Additional occurrences of secondary Co minerals arise through alteration of other minerals, most

84   commonly Ni or Cu chalcogenides, that incorporate minor amounts of cobalt. Spherocobaltite

85   ($CoCO_3$) is a special case, possibly occurring as both a primary phase crystalized from

86   carbonate-rich solutions and as an alteration phase derived from primary Co minerals. However,

87   most specimens occur as crystalline or botryoidal coatings on other phases, based on photos on

88   mindat.org and other sources. Therefore, we include spherocobaltite in the list of secondary

89   minerals.

90   Apart from cobalt itself, twenty-five of the 72 essential chemical elements found in minerals

91   overall (rruff.info/ima; Hazen et al. 2015a) are also essential constituents of cobalt minerals. The

92   most frequently encountered elements (Table 3) are oxygen (in 40 species), hydrogen (37),

93   arsenic (29), and sulfur (22). Next in abundance are metals Fe (8), Ni (7), Cu (6), and Ca (5),

94   while chalcogenides Se and Sb are both represented by 5 species. Forty-six of the mineral-

95   forming elements occur in no known cobalt-bearing minerals; these elements include B, Ba, K,

96   Ti, W, and Zn (all of which are represented in synthetic Co phases; Tables 4 and 5). Note that all

97   but two of the 66 known Co-bearing minerals incorporate O, S, As, and/or Se [the exceptions

98   being kieftite ($CoSb_3$) and mattagamite ($CoTe_2$)]. Fifteen Co minerals incorporate only two

99   different chemical elements [Co plus S (4 species), As (5), Se (3), Sb (1), Te (1), and Fe (1)],

100   whereas   asbolane $[Mn^{4+}(O,OH)_2 \cdot (Co,Ni,Mg,Ca)_x(OH)_{2x} \cdot nH_2O]$,   bouazzerite

101    $[Bi_6(Mg,Co)_{11}Fe_{14}(AsO_4)_{18}O_{12}(OH)_4 \cdot 86H_2O]$, and julienite $[Na_2Co(SCN)_4 \cdot 8H_2O]$ are the most

102   chemically complex Co minerals, each with seven different essential elements. The average for

103   26 primary Co minerals is 2.5 essential elements per species, whereas the 40 secondary phases

104   incorporate an average of 4.8 elements per mineral. The average number of essential elements in

105   66 cobalt minerals is 3.9 elements per species.

106   Coexisting elements in primary cobalt minerals differ markedly from those in secondary

107   minerals in several ways. Oxygen is present in all 40 secondary Co minerals, but in none of the

108   26 primary Co species (with the possible exception of spherocobalitite, which may occasionally

109   occur as a primary phase). All 37 known Co minerals with hydrogen are secondary; only

110   cochromite $(CoCr_2O_4)$, petewilliamsite $[(Ni,Co)_2(As_2O_7)]$, and spherocobaltite are anhydrous

111   secondary minerals.

112

113   COBALT MINERAL ECOLOGY

114   Hystad et al. (2015a) reported that the relationship between the diversity and distribution of

115   mineral species is similar to the frequency distribution of words in a book: typically a few words

116   and phrases occur many times, but most words and phrases are used only once or twice. These

117   rare words and phrases can thus be analyzed to identify the genre and authorship of an unsigned

118   text, and they conform to a Large Number of Rare Event (LNRE) frequency distribution (Baayen

119   2001; Evert and Baroni 2008).

120   We modeled the frequency distribution of cobalt minerals based on the numbers of known

121   localities for each of the 66 approved cobalt minerals. The easiest approach to estimating the

122   number of localities for each species is to interrogate the crowd-sourced data resource

123   mindat.org, which tabulates locality information for every mineral species. This approach was

124   used in the initial mineral ecology studies (Hazen et al. 2015a, 2015b; Hystad et al. 2015a,

125   2015b). For cobalt minerals, we initially analyzed 3662 raw species-locality data from

126   mindat.org (Supplementary Table 1), with 13 species recorded at only one locality, an additional

127   8 species at exactly 2 localities, and 4 species at exactly 3 localities. By contrast, more than half

128   of these species-locality data relate to 3 minerals—cobaltite (762 localities in mindat.org),

129   erythrite (742), and skutterudite (474). The 13 most common cobalt minerals account for 92% of

130   all species-locality data. This distribution of species among localities, with a few common

131   species and many more rare ones, is typical of all minerals, as well as for various subsets of

132   minerals (Hazen et al. 2015a, 2016; Hystad et al. 2015b; Grew et al. 2016b). These data fit to

133   both a finite Zipf-Mandelbrot (fZM) and a Generalized Inverse Gauss-Poisson (GIGP) model

134   (Hystad et al. 2015a; Supplement Text 1). The GIGP parameters for Co minerals (γ = -

135   0.2853056; B = 0.03610296; C = 0.2432292; P-value = 0.81; Hystad et al. 2015a) facilitate

136   modeling of the Co-mineral accumulation curve (Supplemental Figure 1), with a prediction of a

137   total of at least 87 cobalt minerals. By this estimate, at least 21 Co-bearing minerals occur on

138   Earth but have not yet been described.

139   Grew et al. (2016b) noted that uncritical use of locality data from mindat.org can lead to

140   errors for two reasons. In some cases mindat.org does not list all known localities, leading to

141   underestimates of the number of localities. Thus, for example, mindat.org lists only 2 localities

142   (in Canada and Finland) for mattagamite ($CoTe_2$); however, a systematic search of Georef

143   reveals another report of an Australian occurrence, for a corrected total of 3 localities. In other

144   instances mindat.org lists too many localities because many of the distinct "localities" in

145   mindat.org refer to specimens from different specific outcrops, veins, or quarries within a single

146   ore body or mineralized zone, and thus should be treated as only 1 locality. Thus, the 9

147   mindat.org localities for cobaltlotharmeyerite [$CaCo_2(AsO_4)_2 \cdot 2H_2O$] in fact represent only two

148   mineralization events—the Bou Azer District in Morocco, and the Schneeberg District of

149   Saxony, Germany.

150   A relatively fast and straightforward approach to improved locality counts is to eliminate the

151   geographically redundant mindat.org localities, while adding missing localities cited in the

152   *Handbook of Mineralogy* but not in mindat.org. The resulting 3525 locality counts

153   (Supplementary Table 1) include 13 species from only one locality, an additional 10 species

154 from exactly 2 localities, and 6 species from exactly 3 localities. These data fit to both fZM and

155 GIGP models. The GIGP parameters (γ = -0.6325573; B = 0.02307183; C = 2.189657; P-value =

156 0.38; Hystad et al. 2015a) lead to a prediction of at least 80 cobalt minerals (see Supplemental

157 Figure 2). This improved estimate of 14 "missing" Co-bearing minerals is significantly smaller

158 than that obtained from the uncritical use of mindat.org data noted above.

159   Grew et al. (2016a) argue that the most valid approach to determining the numbers of

160 localities for each species is an exhaustive search of the primary literature for all but the most

161 common species. (The exact locality counts for minerals known from more than 15 localities

162 have little effect on LNRE models, which depend on the rarest species.) Therefore, we searched

163 the primary literature for confirmation of every cobalt mineral locality for species with 50 or

164 fewer localities reported on mindat.org—a task that required examination of approximately 1000

165 primary references. In the process we discovered 41 new localities distributed among 19 rare

166 cobalt minerals, while eliminating 12 unconfirmed species-locality data. The resulting total of

167 3554 mineral species-locality data (Table 1) includes 13 species from only one locality, with an

168 additional 8 species from exactly 2 localities, and 7 species from exactly 3 localities. These data

169 fit to both fZM and GIGP models. The GIGP parameters (γ = -0.4938359; B = 0.03418968; C =

170 0.701821; P-value = 0.96; Hystad et al. 2015a) lead to a prediction of at least 81 cobalt minerals

171 (Figure 1). This model, and its estimate of 15 "missing" Co-bearing minerals, is nearly identical

172 to that obtained by the simpler procedure of modifying mindat.org locality counts and adding

173 additional localities from the *Handbook of Mineralogy*. However, it remains to be seen whether

174 the simpler protocols are adequate for all mineral groups.

175   Note that our prediction of 15 Co minerals yet to be discovered is a minimum estimate

176 because it assumes that cobalt minerals will continue to be discovered employing the same

177   techniques as in the past. However, we suggest that a significant number of Co minerals have yet

178   to be discovered by application of microanalytical techniques. Presently, an unusually high

179   percentage of known Co minerals (55 of 66, or 83%) can be identified by their distinct color

180   and/or morphology in hand specimen or with a hand lens. The relatively small percentage (16%)

181   of Co minerals discovered by microanalytical techniques contrasts with minerals of many other

182   elements, including Na and Te, for which as many as 50% of species have been discovered

183   through microanalysis (Hazen et al. 2015b). Therefore, we suggest that dozens of additional Co

184   minerals await discovery through micro-Raman spectroscopy, electron microprobe analysis,

185   and/or electron microscopy—species that would not be reflected in our accumulation curve

186   (Figure 1b).

187

THE "MISSING" MINERALS OF COBALT

189   The 66 known minerals of cobalt represent a small fraction of the thousands of known

190   inorganic Co compounds [Mellor 1935; International Crystal Structure Database (http://icsd.fiz-

191   karlsruhe.de)]. Hazen et al. (2015a) suggested that every chemical element has the potential to

192   form at least 1000 mineral species; however, relatively rare elements tend to form fewer mineral

193   species because of the special geochemical conditions required to concentrate those elements

194   (Christy 2015; Hazen et al. 2015b). Accordingly, Table 4 records 33 primary and Table 5 lists

195   117 secondary mineral-like synthetic Co compounds that have not been reported in nature, but

196   which might occur in the inventory of as yet undiscovered cobalt minerals on Earth (or on other

197   highly differentiated planets).

198   As a rare element that mimics the crystal chemistry of several other more common transition

199   elements, including Fe, Ni, and Cu, most cobalt in Earth's crust is probably distributed as a

200   minor element in more common phases, most notably pyrite and other sulfides, but also oxides

201   (notably spinel; Chauviré et al. 2015; Lenaz et al. 2015) and silicates, including pyroxene and

202   olivine (White et al. 1971; Morimoto et al. 1974; Mantovani et al. 2014). As a consequence,

203   cobalt displays far fewer species than might be predicted from its crustal abundance (Christy

204   2015; Hazen et al. 2015). Only when Co is locally concentrated do phases with essential Co

205   crystallize.

206   Synthetic cobalt phases point to plausible as yet undiscovered minerals. Table 4 lists 33 Co

207   chalcogenides that possess the same structural topologies and incorporate the same elements as

208   known minerals. These phases include 9 marcasite-type, 8 pyrite-type, 7 nickeline-type, and 4

209   spinel-type compounds—all of which are structures represented by common cobalt minerals.

210   These synthetic phases also incorporate the same transition elements—Cr, Cu, Fe, and Ni—that

211   are found in primary Co minerals.

212   Secondary cobalt minerals are compositionally more diverse, though all incorporate oxygen,

213   and all but two minerals incorporate hydrogen as an essential element. These compositional

214   characteristics are reflected in our list of 117 plausible Co minerals that are known as synthetic

215   compounds but have not yet been discovered in nature (Table 5). These cobalt compounds

216   include CoO, well-known as a synthetic phase with the rocksalt structure (e.g., Roth 1958;

217   Sumino et al. 1980; Armentrout et al. 2013), as well as two other oxides (spinel-type Co_3O_4 and

218   alumina-type Co_2O_3) and cobaltous hydroxide [$Co^{2+}(OH)_2$] with the brucite structure. We also

219   tabulate 11 plausible cobalt double oxides, all of which incorporate either Ca or a second

220   transition element.

221   Only one cobalt silicate mineral has been approved by the IMA: oursinite

222   [$Co(UO_2)_2(SiO_3OH)_2 \cdot 6H_2O$], known from a single locality in the Democratic Republic of the

223   Congo. A second potential cobalt silicate mineral is the Co-dominant analogue of staurolite,

224   "lusakite," which was reported from near Lusaka, Zambia (Skerl et al. 1934); cobaltian staurolite

225   has been described from Lusaka and Samos, Greece (Čech et al. 1981; Bringhurst and Griffen

226   1986; Taran et al. 2009). Phillips and Griffen (1986) synthesized the series staurolite-"lusakite"

227   over the entire range of Co/(Co+Fe) from 0 to 1. In addition, several other synthetic cobalt

228   silicates are known, notably cobaltian tourmaline (Taran et al. 1993; Setkova et al. 2009) and

229   isomorphs of spinel, olivine, garnet, and pyroxene (e.g., Kohn and Eckart 1962; Geller 1963,

230   White et al. 1971; Morimoto et al. 1974). Cobalt often substitutes as a trace element for Mg-Fe in

231   natural analogues of these and other structures, but has not yet been found as the dominant

232   cation. For example, from 1 to 7 wt% CoO has been found in högbomite, zincohögbomite,

233   gahnite, ilmenite, magnetite, rhodonite and Ni-dominant chlorite (Čech et al. 1976, 1981; Silaev

234   and Yanulova 1993; Taran et al. 1989; Feenstra 1997; Feenstra et al. 2003).

235   Only one cobalt halide has been documented, the chloride leverettite [$Cu_3CoCl_2(OH)_6$], which

236   is known from a single locality. Many additional synthetic fluorides and chlorides are known,

237   most of which are hydrous compounds (Table 5).

238   Twenty-nine of the 40 known secondary cobalt minerals are sulfates, arsenates, or selenates.

239   Table 5 records 38 additional examples known only as synthetic compounds. The majority of

240   these synthetics, as with known minerals, are hydrous. All of these phases also incorporate other

241   essential elements that occur in Co minerals, but we also list phases with potassium and

242   barium—elements that are well documented in synthetic cobalt compounds but not yet known in

243   natural examples.

244   Two secondary hydrous carbonates have been described—the rare minerals comblainite

245   [$Ni_6Co^{3+}_2CO_3(OH)_{16} \cdot 4H_2O$] and kolwezite [$CuCoCO_3(OH)_2$]. At least five additional mineral-

246   like hydrous cobalt carbonates are known as synthetic compounds.

247   Only one cobalt phosphate is known in nature: pakhomovskyite [$Co_3(PO_4)_2 \cdot 8H_2O$], found

248   only on the Kola Penisula of Russia. Nevertheless, numerous synthetic Co phosphates have been

249   described (36 of which appear in Table 5) and they point to the potential diversity if a deposit

250   enriched in Co + P were to be discovered. In addition to 9 hydrous Co phosphates, compounds

251   with Na, K, Mg, Ba, and several transition metals demonstrate the potential richness of these as

252   yet undiscovered phases.

253   A number of synthetic cobalt compounds incorporate elements that have not yet been found to

254   coexist with Co in any mineral species, but are plausible as candidates for as yet undiscovered

255   natural phases. Most notably, these elements include potassium, which is known in dozens of

256   synthetic cobalt halides, sulfates, selenates, carbonates, and phosphates. Other likely candidate

257   elements in Co minerals include boron, barium, zinc, chlorine, and titanium, all of which are

258   known in mineral-like synthetic Co compounds.

259   Note that we do not include Co^{4+} compounds, which have not yet been found in nature, but

260   have been synthesized in a variety of phases, including cobalt dioxide, CoO_2, and a variety of

261   "percobaltites" such as Na_2CoO_3, $BaCo_2O_5$, and $MgCoO_3$. The absence of natural Co^{4+} minerals

262   is likely due to the fact that tetravalent cobalt requires redox conditions that are unlikely in any

263   crustal environment, much less in Earth's mantle.

264   This survey of plausible as yet undiscovered cobalt minerals points to strategies for the

265   discovery of new Co phases. In particular, the 10 localities with 10 or more Co mineral species

266   (Table 2) are especially rich in unusual species; they include type localities for 26 of 66 approved

267 cobalt minerals. Close examinations of specimens from those localities, several of which are

268 flooded or otherwise no longer accessible, are likely to yield additional cobalt minerals.

269

270 **IMPLICATIONS: MINERAL ECOLOGY OF A TRACE ELEMENT**

271 Previous studies in mineral ecology have focused on elements, including beryllium, boron,

272 and carbon (Grew and Hazen 2014; Grew et al. 2016a, Hazen et al. 2016), that have unique

273 crystal chemical characteristics and thus tend to concentrate in their own minerals. Cobalt, by

274 contrast, is the first element to be studied with this methodology that usually mimics more

275 common elements—most notably magnesium, iron, and nickel—rather than form its own

276 minerals. For example, ocean basalt, with total volume $\sim 3 \times 10^9$ km^3 and density ~ 3 gm/cm^3 (and

277 therefore total mass $\sim 9 \times 10^{24}$ gm), has an average Co content of 48 ppm, with up to 150 ppm in

278 olivine (Herzberg et al. 2016). Ocean basalt thus holds $\sim 4 \times 10^{14}$ metric tons of cobalt—more

279 than 50,000,000 times greater than the 2016 United States Geological Survey estimate of world

280 cobalt ore reserves ($\sim 7.1 \times 10^6$ tons; http://minerals.usgs.gov). Even the most common primary

281 Co minerals, such as cobaltite and skutterudite, are volumetrically insignificant by comparison.

282 One might expect, therefore, that cobalt minerals display a different frequency distribution than

283 minerals of more common elements, or of rare elements that are not readily incorporated as

284 minor constituents of common rock-forming minerals.

285 Our results suggest that, on the contrary, the minerals of cobalt conform to a robust LNRE

286 distribution that facilitates predictions of the numbers of as yet undiscovered Co mineral species,

287 just as an LNRE distribution does for all minerals in Earth's crust (Hazen et al. 2015a). We

288 conclude that other subsets of minerals grouped by both major and minor elements could also

289   conform to a LNRE distribution: the viability of LNRE modeling for boron minerals is currently

290   under study (Grew et al. 2016a).

291   More general questions concern the underlying reasons for this fascinating statistical feature

292   of minerals on Earth, and whether similar distributions occur on other worlds. In particular, the

293   majority of rare cobalt minerals are secondary phases that arise from near-surface oxidation;

294   these minerals are thus indirect consequences of biological processes. Studies in progress will

295   explore whether the observed LNRE distributions of Earth's minerals are uniquely a

296   consequence of rare biologically-mediated species and, consequently, if LNRE distributions are

297   an unambiguous mineralogical signature of life on Earth-like planets.

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427

428 **Table 3.** Coexisting essential elements in cobalt minerals, including elements in the 26 primary
429 versus 40 secondary species. Numbers for 25 elements are based on mineral species and
430 chemical formulas in rruff.info/ima as of 1 March 2016.

431

Element	# 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

458

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

463

Formula	Structure Type	Related known minerals
Sulfides		
$NiCo_2S_4$	Spinel	Co_3S_4 (linnaeite); $CuCo_2S_4$ (carrollite);
$CoCr_2S_4$	Spinel	$CoNi_2S_4$ (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_8FeS_8	Pentlandite	Co_9S_8 (cobaltpentlandite)
Arsenides		
$CoAs_2$	Arsenopyrite	(Co,Fe)AsS (glaucodot)
CoAsSe	Pyrite	$CoSe_2$ (trogtalite)
$CoAs_2$	Marcasite	
CoAsSe	Marcasite	
Co_2AsSb	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_9Se_8	Pentlandite	
$CoSe_2$	Marcasite	
CoSbSe	Marcasite	
$CoCr_2Se_4$	Spinel	Co_3Se_4 (bornhardtite);
Co_2NiSe_4	Spinel	$(Co,Cu,Ni)_3Se_4$ (tyrrellite)
$CoFe_2Se_4$	Wilkmanite	

493	$CoNi(Se_2)_2$	Pyrite	
494	$CoNiSe_2$	Nickeline	CoSe (freboldite)
495			
496	*Antimonides*		
497	CoSb	Nickeline	
498	$CoSb_2$	Marcasite	
499	$Co_{0.5}Fe_{0.5}Sb_2$	Marcasite	
500	CoSbTe	Marcasite	
501	$CoSb_2$	Monoclinic $CoSb_2$	
502			
503	*Tellurides*		
504	CoTe	Nickeline	
505	$CoNiTe_2$	Nickeline	
506	$CoTe_2$	Pyrite	
507	$CoNi(Te_2)_2$	Pyrite	

508 _____

509

510

511

512 **TABLE 5.** Plausible as yet undescribed secondary cobalt minerals, based on synthetic Co-bearing phases

513 tabulated in the International Crystal Structure database that incorporate oxygen and from 1 to 5

514 additional chemical elements (Table 1).

515

Formula	Structure Type
Co Single Oxides/Hydroxides	
CoO	Halite
CoO_2	CdI_2
Co_3O_4	Spinel
$Co(OH)_2$	Brucite
Double Oxides	
$NiCo_2O_4$	Spinel
$CoFe_2O_4$	Spinel
$MnCo_2O_4$	Spinel
$CoCu_2O_3$	
Ca_2CoO_3	
$CaCo_2O_4$	Harmunite
$CoMnO_3$	
$CoTiO_3$	Ilmenite
$CoCrO_4$	$CrVO_4$
$CoMoO_4$	
$CoWO_4$	
Silicates/Aluminates	
Co_2SiO_4	Spinel
$CoAl_2O_4$	Spinel
Co_2SiO_4	Olivine
$MgCoSiO_4$	Olivine
$Ca_2Co(Si_2O_7)$	Akermanite
$Co_3Al_2Si_3O_{12}$	Garnet
$CaCo(Si_2O_6)$	Diopside
$Na_2Co(Si_4O_{10})$	Layer silicate
Fluorides	

516 Formula / Structure Type
517
518 Co Single Oxides/Hydroxides
519 CoO / Halite
520 CoO₂ / CdI₂
521 Co₃O₄ / Spinel
522 Co(OH)₂ / Brucite
523 Double Oxides
524 NiCo₂O₄ / Spinel
525 CoFe₂O₄ / Spinel
526 MnCo₂O₄ / Spinel
527 CoCu₂O₃
528 Ca₂CoO₃
529 CaCo₂O₄ / Harmunite
530 CoMnO₃
531 CoTiO₃ / Ilmenite
532 CoCrO₄ / CrVO₄
533 CoMoO₄
534 CoWO₄
535 Silicates/Aluminates
536 Co₂SiO₄ / Spinel
537 CoAl₂O₄ / Spinel
538 Co₂SiO₄ / Olivine
539 MgCoSiO₄ / Olivine
540 Ca₂Co(Si₂O₇) / Akermanite
541 Co₃Al₂Si₃O₁₂ / Garnet
542 CaCo(Si₂O₆) / Diopside
543 Na₂Co(Si₄O₁₀) / Layer silicate
544 Fluorides

545	CoF_2	
546	$CoF_2 \cdot H_2O$	
547	$Co_2OF_2 \cdot H_2O$	
548	K_2CoF_4	
549	$KCoF_3 \cdot H_2O$	
550	$NaCoF_3 \cdot H_2O$	
551	$AlCoF_5 \cdot 7H_2O$	
552	$CoF_3 \cdot nH_2O$	
553	*Chlorides*	
554	$CoCl_2$	
555	$CoCl_2 \cdot H_2O$	
556	$Co(OH)Cl$	
557	$Co_2(OH)_3Cl$	
558	$MgCoCl_4 \cdot 8H_2O$	
559	$Zn_2CoCl_6 \cdot 12H_2O$	
560	$ZnCoCl_4 \cdot 6H_2O$	
561	*Sulfates*	
562	$CoSO_4$	
563	$Co_3(SO_4)_2(OH)_2 \cdot 2H_2O$	
564	$Co_5(SO_4)_2(OH)_6 \cdot 4H_2O$	
565	$NaCo(SO_4)F$	
566	$NaCo_2(SO_4)_2(H_2O)(OH)$	
567	$K_2Co_2(SO_4)_3$	
568	$K_2Co(SO_4)_2 \cdot 2H_2O$	
569	$K_2Co(SO_4)_2 \cdot 6H_2O$	
570	$CoNi(SO_4)_2 \cdot 12H_2O$	
571	$Co(UO_2)(SO_4)_2 \cdot 5H_2O$	
572	*Arsenates*	
573	$Co_3(AsO_4)_2$	
574	$Co_2As_2O_5$	
575	$Co_2As_2O_7$	Thortveitite
576	$Co_2(AsO_4)(OH)$	Andalusite
577	$Co_2(As_2O_7) \cdot 2H_2O$	
578	$Co_2(AsO_4)Cl$	

579	$BaCo_2(AsO_4)_2$	
580	$Co(UO_2)_2(AsO_4)_2 \cdot 12H_2O$	
581	*Selenates*	
582	$Co(SeO_4 \cdot H_2O$	
583	$Co(SeO_4) \cdot 5H_2O$	
584	$Co(SeO_3) \cdot H_2O$	
585	$Co(HSeO_3)_2 \cdot 2H_2O$	
586	$Co(HSeO_3)_2 \cdot 4H_2O$	
587	$Co_3(SeO_3)_3 \cdot H_2O$	
588	$Co_5(SeO_3)_4Cl_2$	
589	$Co(HSeO_3)Cl \cdot 2H_2O$	
590	$Co(HSeO_3)Cl \cdot 3H_2O$	
591	$Na_2Co(SeO_4)_2 \cdot 2H_2O$	Fairfieldite
592	$K_2Co_2(SeO_3)_3$	
593	$K_2Co_2(SeO_3)_2(OH)$	
594	$K_2Co_2(SeO_3)_3 \cdot 2H_2O$	
595	$K_2Co(SeO_4)_2 \cdot 2H_2O$	
596	$K_2Co(SeO_4)_2 \cdot 6H_2O$	
597	$Ca_3Co(SeO_3)_4$	
598	$BaCo(SeO_3)_2$	
599	$BaCo_2(SeO_3)_3 \cdot 3H_2O$	
600	$Co_3Fe_2(SeO_3)_6 \cdot 2H_2O$	
601	$Co_2(UO_2)_3(SeO_4)_5 \cdot 16H_2O$	
602	*Carbonates*	
603	$Co_2(CO_3)(OH)_2$	
604	$K_2Co(CO_3)_2(H_2O)_4$	
605	$Na_2Co(CO_3)_2(H_2O)_4$	
606	$Ba_2Co(CO_3)_2F_2$	
607	$Na_3Co(CO_3)_2Cl$	
608	*Phosphates*	
609	$CoPO_4$	
610	$Co_3(PO_4)_2$	Chopinite
611	$Co_3(PO_4)_2(H_2O)$	
612	$Co_3(PO_4)_2(H_2O)_6$	

613	$Co_3(HPO_4)_2(OH)_2$	Lazulite
614	$Co_3(PO_4)_2(H_2O)_4$	
615	$Co_2(PO_4)(OH)$	
616	$Co_2(PO_4)_2(OH)_4$	
617	$Co_5(PO_4)_2(OH)_4$	
618	$Co(HPO_4)(H_2O)$	
619	$Co(H_2PO_4)_2(H_2O)_2$	
620	$Co_2(PO_4)Cl$	
621	$NaCo(PO_4)$	Olivine
622	$NaCo_4(PO_4)_3$	
623	$NaCo_3(PO_4)_2(OH)·H_2O$	
624	$Na_2Co(PO_4)F$	
625	$KCo(PO_4)$	Andalusite
626	$K_2Co(PO_4)_3$	
627	$KCo_4(PO_4)_3$	
628	$KCoAl(PO_4)_2$	
629	$KCo_3Fe(PO_4)_3$	
630	$KCo_2(PO_4)_2·H_2O$	
631	$KCo(PO_4)·H_2O$	
632	$Mg_3Co_3(PO_4)_4$	
633	$BaCo_2(PO_4)_2$	
634	$Co(TiO)_2(PO_4)$	
635	$Zn_2Co(PO_4)_2$	
636	$Zn_3Co_3(PO_4)_4$	
637	$ZnCo(PO_4)(OH)$	
638	$CoZn_2(PO_4)_2.4H_2O$	
639	$CoFe(PO_4)O$	Sillimanite
640	$Co_2Fe(PO_4)_2$	
641	$Co_3Cr_4(PO_4)_6$	
642	$FeCo(PO_4)F$	
643	$Co_3(BO_3)(PO_4)$	
644	$Co(UO_2)_2(PO_4)_2·10H_2O$	

645 _____

646

647   **Figure 1.** (*a*) Frequency spectrum analysis of 66 cobalt-bearing minerals, with 3554 individual

648   mineral-locality data (from mindat.org as of 1 March 2016), employed a Generalized Inverse

649   Gauss-Poisson (GIGP) function to model the number of mineral species for minerals found at

650   exactly 1 to 5 localities (Hystad et al. 2015a). (*b*) This model facilitates the prediction of the

651   mineral species accumulation curve (upper curve, "All"), which plots the number of expected Co

652   mineral species (*y*-axis) as additional mineral species/locality data (*x*-axis) are discovered. The

653   vertical dashed line indicates data recorded as of 1 March 2016 in mindat.org, as well as locality

654   data from the *Handbook of Mineralogy* (Anthony et al. 2003) and systematic searching under

655   each mineral name in Georef. The model also predicts the varying numbers of mineral species

656   known from exactly one locality (curve 1) or from exactly two localities (curve 2). Note that the

657   number of mineral species from only one locality is now decreasing, whereas the number from

658   two localities is now increasing, but is almost at a maximum and will eventually decrease. We

659   predict that the number of minerals known from two localities will surpass those from one

660   locality when the number of species-locality data exceeds ~9000.

661

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 underscored).

# Name (# Localities)	Formula	Paragenetic Mode	Select Localities (see Table 2 for key)
Primary Co Minerals			
1 Alloclasite (37)	CoAsS	Low-T hydrothermal	1,3,4,6,9,10,20,24,27,28,51
2 Bornhardite (3)	$Co^{2+}Co^{3+}_2Se_4$	Hydrothermal	31
3 Carrollite (127)	$CuCo_2S_4$	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-T 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_9S_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	41
10 Freboldite (4)	CoSe	Hydrothermal; carbonate hosted	31
11 Glaucodot (108)	$Co_{0.5}Fe_{0.5}AsS$	High-T hydrothermal	1,2,4,10,16,25,27,28,42,51
12 Jaipurite (4)	CoS	Hydrothermal ore	43
13 Kieftite (3)	$CoSb_3$	Sulfide skarn	1,7
14 Langisite (5)	CoAs	Hydrothermal zone	6
15 Linnaeite (181)	Co_3S_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	45
18 Oenite (1)	CoSbAs	Cu-Co skarns	7
19 Paracostibite (7)	CoSbS	Massive sulfide; hydrothermal	47

20 Safflorite (266)	$CoAs_2$	Moderate-T 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)	$CoNi_2S_4$	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-T 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	31
24 Tyrrellite (9)	$(Co,Cu,Ni)_3Se_4$	Hydrothermal ore	52
25 Wairauite (8)	$CoFe$	Serpentinization	65
26 Willyamite (16)	$CoSbS$	Carbonate-hosted veins	4,7,15,25

Secondary Co Minerals

27 Aplowite (5)	$CoSO_4 \cdot 4H_2O$	Efflorescences with sulfides	11,29,46
28 Asbolane (122)	$Mn^{4+}(O,OH)_2 \cdot (Co,Ni,Mg,Ca)_x(OH)_{2x} \cdot nH_2O$	Weathering; ultramafic soils	1,2,3,4,5,9,10,11,12,16,21,23,24,26,36,39,42,48
29 Bieberite (53)	$CoSO_4 \cdot 7H_2O$	Oxidation of S-As ores	2,3,10,11,14,23,24,30,39
30 Bouazzerite (1)	$Bi_6(Mg,Co)_{11}Fe_{14}(AsO_4)_{18}O_{12}(OH)_4 \cdot 86H_2O$	Oxidation of ores	1
31 Burgessite (2)	$Co_2(H_2O)_4(AsO_3OH)_2 \cdot H_2O$	Secondary weathering zone	6
32 Cobaltarthurite (3)	$CoFe^{+3}_2(AsO_4)_2(OH)_2 \cdot 4H_2O$	Weathered zone	1,33
33 Cobaltaustinite (5)	$CaCoAsO_4(OH)$	Oxidized zone of ores	1,2,11,34
34 Cobaltkieserite (2)	$CoSO_4 \cdot H_2O$	Oxidized ore	3,35
35 Cobaltkoritnigite (17)	$Co(AsO_3OH) \cdot H_2O$	Weathering of glaucodot	1,2,3,8,9,21,36
36 Cobaltlotharmeyerite (2)	$CaCo_2(AsO_4)_2 \cdot 2H_2O$	Oxidized ore	1,2
37 Cobaltneustädtelite (2)	$Bi_2Fe^{3+}(Co,Fe^{3+})(AsO_4)_2(O,OH)_4$	Oxidized ore	2
38 Cobaltoblodite (1)	$Na_2Co(SO_4)_2 \cdot 4H_2O$	Oxidized ore	39
39 Cobaltomenite (6)	$CoSe^{4+}O_3 \cdot 2H_2O$	Oxidized ore	5,37
40 Cobalttsumcorite (1)	$PbCo_2(AsO_4)_2 \cdot 2H_2O$	Oxidized ore	2
41 Cobaltzippeite (2)	$Co(UO_2)_2(SO_4)O_2 \cdot 3.5H_2O$	Oxidized ore	3,39

42 Cochromite (3)	$CoCr_2O_4$	Thermal metamorphism of chromite	40
43 Comblainite (4)	$Ni_6Co^{3+}_2CO_3(OH)_{16}\cdot 4H_2O$	Oxidized ore	5,31
44 Erythrite (742)	$Co_3(AsO_4)_2\cdot 8H_2O$	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)	$(Ni,Co)Cu_4(AsO_4)_2(AsO_3OH)_2$	Oxidized ore	1
47 Jamborite (17)	$Ni^{2+}_{1-x}Co^{3+}_x(OH)_{2-x}(SO_4)_x\cdot nH_2O$ $[x \leq 1/3; n \leq (1-x)]$ Oxidized ore	54
48 Julienite (1)	$Na_2Co(SCN)_4\cdot 8H_2O$	Incrustations on talc schist	5
49 Karpenkoite (1)	$Co_3(V_2O_7)(OH)_2\cdot 2H_2O$	Oxidized ore	55
50 Kolwezite (6)	$CuCoCO_3(OH)_2$	Oxidized ore	5
51 Leverettite (1)	$Cu_3CoCl_2(OH)_6$	Oxidized ore	56
52 Metakirchheimerite (2)	$Co(UO_2)_2(AsO_4)_2\cdot 8H_2O$	Oxidized ore	3,9
53 Moorhouseite (12)	$CoSO_4\cdot 6H_2O$	Effluoresces with S	1,2,3,9,11,14,29
54 Neustädtelite (4)	$Bi_2Fe^{3+}(Fe^{3+},Co)_2(AsO_4)_2(O,OH)_4$	Oxidized ore	2,22
55 Oursinite (1)	$Co(UO_2)_2(SiO_3OH)_2\cdot 6H_2O$	Secondary mineral	5
56 Pakhomovskyite (1)	$Co_3(PO_4)_2\cdot 8H_2O$	Carbonatite alteration	46
57 Petewilliamsite (1)	$(Ni,Co)_{30}(As_2O_7)_{15}$	Oxidized ore	48
58 Pradetite (2)	$CoCu_4(AsO_4)_2(AsO_3OH)_2\cdot 9H_2O$	Oxidized ore	3,49
59 Rappoldite (1)	$PbCo_2(AsO_4)_2\cdot 2H_2O$	Oxidized ore	2
60 Roselite (15)	$Ca_2Co(AsO_4)_2\cdot 2H_2O$	Oxidized ore	1,2,4,8,9,34
61 Roselite-beta (9)	$Ca_2Co(AsO_4)_2\cdot 2H_2O$	Oxidized ore	1,2,4,8
62 Schneebergite (3)	$BiCo_2(AsO_4)_2(OH)\cdot H_2O$	Oxidized ore	2
63 Smolyaninovite (11)	$Co_3Fe^{3+}_2(AsO_4)_4\cdot 11H_2O$	Oxidized ores	1,2,4,24,34,35,51
64 Spherocobaltite (21)**	$CoCO_3$	Carbonate alteration	1,2,5,11,14,22,26,54

4

65 Thérèsemagnanite (2)	$Co_6SO_4(OH)_{10}{\cdot}8H_2O$	Oxidized ore	49
66 Wupatkiite (7)	$CoAl_2(SO_4)_4{\cdot}22H_2O$	Oxidized zone	4,14

*Locality data compiled from MinDat.org as of 1 March 2016.

**Spherocobaltite may also occur as a primary mineral.

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. Listed are all localities with at least 7 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.

Locality	#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,<u>30</u>, 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,<u>20</u>,22;** <u>28</u>,29,33,35,<u>36,37</u>,40, <u>44</u>,45,53,<u>54,59,60,61,62,63</u>,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,<u>46</u>,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,<u>43</u>,44,45,<u>48</u>, 50,<u>55</u>,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,<u>5</u>,6,7,11,<u>14</u>,20,21,22;** <u>31</u>,44,45)	Hydrothermal Ag-Co-Ni-Cu-As-S quartz-calcite veins
7. Tunaberg, Nyköping, Södermanland, Sweden	11 (**3,6,7,8,<u>13</u>,15,<u>18</u>,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,<u>52</u>,53,60)	Ag-Bi-Co-Ni-U mineralization in granite
10. Siegerland, North Rhine-Westphalia, Germany	11 (**1,3,6,11,15,20,<u>21</u>,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, USA	8 (**15,21,22;** 29,44,53,64,<u>66</u>)	U mineralization
15. Broken Hill, Yancowinna Co., New South Wales, Australia	7 (**6,<u>8</u>,15,20,22,<u>26</u>;** 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**)	
18. Zhongtiaoshan ore field, Yuanqu County, Yuncheng Prefecture, China	7 (**3,4,6,7,15,21;** 44)	
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-Wurttemberg, 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-	7 (**1,22;** 28,29,44,45,63)	

Velha, Aveiro District, Portugal

25. Hnúšťa, Rimavská Sobota County, Banská Bystrica Region, Slovakia   7 (**3,8,11,15,21,26;** 44)

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 (<u>**1**</u>**,3,6,7,11**)

29. Walton Barite Mine, Hants County, Nova Scotia, Canada   3 (<u>27</u>,44,<u>53</u>)   Barite, Pb-Zn-Cu; Co incidental

30. Bieber, Hesse, Germany   5 (**6,20,22;** <u>29</u>,44)

31. Lautenthal, Harz, Lower Saxony, Germany   6 (**2,6,**<u>**10**</u>**,23;** 43,44)   Veins with 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,**<u>**15**</u>**;** <u>34</u>,44,63)

36. Schwarzenberg District, Erzgebirge, Saxony, Germany   5 (**20,22;** 28,<u>35</u>,44)

37. Cerro de Cacheuta, Mendoza, Argentina   1 (<u>39</u>)   Cu deposit in ultramafics; Co incidental

38. Varislahti deposit, South Karelia,   1 (<u>**7**</u>)   Cu-Ni-Co-Fe-S

Southern Finland, Finland

39. White Canyon District, San Juan County, Utah	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,<u>9</u>,15,20**)	
42. Huasco, Atacama Region, Chile	6 (**3,6,<u>11</u>;** 28,44,45)	Cu with Co-U veins in diorite.
43. Jhunjhunu District, Rajasthan, India	2 (**6,<u>12</u>**)	Cu-Co-S veins
44. Mattagami, Nord-du-Québec, Québec, Canada	2 (**6,<u>16</u>**)	Co
45. Witwatersrand field, Gauteng/ Mpumalanga Provinces, South Africa	2 (**6,<u>17</u>**)	
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,<u>19</u>**)	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 (44,53,<u>58</u>,<u>65</u>)	Co minerals all secondary
50. Skutterud and nearby Mines, Modum, Buskerud, Norway	6 (**3,6,11,15,<u>22</u>;** 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**,<u>**24**</u>)	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, Emila-Romagna, Italy	3 (**15**; <u>47</u>,64)	
55.	Yellow Cat District, Grand County, Utah	1 (<u>49</u>)	
56.	El Tamarugal Province, Tarapaca Region, Chile	2 (**6**; <u>51</u>)	