

1 REVISION #1A—June 26, 2021—Submitted to *American Mineralogist*

2
3 **On the paragenetic modes of minerals:**
4 **A mineral evolution perspective**

5
6 **ROBERT M. HAZEN^{1,*} AND SHAUNNA M. MORRISON¹**

7 ¹Earth and Planets Laboratory, Carnegie Institution for Science,
8 5251 Broad Branch Road NW, Washington DC 20015, U. S. A.

9
10 **ABSTRACT**

11 A systematic survey of 57 different paragenetic modes distributed among 5659 mineral
12 species reveals patterns in the diversity and distribution of minerals related to their
13 evolving formational environments. The earliest minerals in stellar, nebular, asteroid, and
14 primitive Earth contexts were dominated by relatively abundant chemical elements,
15 notably H, C, O, Mg, Al, Si, S, Ca, Ti, Cr, and Fe. Significant mineral diversification
16 subsequently occurred via two main processes, first through gradual selection and
17 concentration of rarer elements by fluid-rock interactions (for example, in hydrothermal
18 metal deposits, complex granite pegmatites, and agpaitic rocks), and then through near-
19 surface biologically-mediated oxidation and weathering.

20 We find that 3349 mineral species (59.2 %) are known from only one paragenetic
21 context, whereas another 1372 species (24.2 %) are associated with two paragenetic
22 modes. Among the most genetically varied minerals are pyrite, albite, hornblende,
23 corundum, magnetite, calcite, hematite, rutile, and baryte, each with 15 or more known
24 modes of formation.

25 Among the most common paragenetic modes of minerals are near-surface

26 weathering/oxidation (1998 species), subsurface hydrothermal deposition (859 species),
27 and condensation at volcanic fumaroles (459 species). In addition, many species are
28 associated with compositionally extreme environments of highly differentiated igneous
29 lithologies, including agpaitic rocks (726 species), complex granite pegmatites (564
30 species), and carbonatites and related carbonate-bearing magmas (291 species).
31 Biological processes lead to at least 2707 mineral species, primarily as a consequence of
32 oxidative weathering but also through coal-related and other taphonomic minerals (597
33 species), as well as anthropogenic minerals, for example as byproducts of mining (603
34 minerals). However, contrary to previous estimates, we find that only ~34% of mineral
35 species form *exclusively* as a consequence of biological processes. By far the most
36 significant factor in enhancing Earth's mineral diversity has been its dynamic
37 hydrological cycle. At least 4583 minerals – 81 % of all species – arise through water-
38 rock interactions.

39 A timeline for mineral-forming events suggests that much of Earth's mineral diversity
40 was established within the first 250 million years. If life is rare in the universe, then this
41 view of a mineralogically diverse early Earth provides many more plausible reactive
42 pathways over a longer timespan than previous models. If, however, life is a cosmic
43 imperative that emerges on any mineral- and water-rich world, then these findings
44 support the hypothesis that life on Earth developed rapidly in the early stages of planetary
45 evolution.

46 _____
47 *E-mail: rhazen@carnegiescience.edu. ORCID 0000-0003-4163-8644

48 **Keywords:** philosophy of mineralogy; classification; mineral evolution; natural kinds;
49 meteorite mineralogy; thermal metamorphism; aqueous alteration; biomineralization

50

INTRODUCTION

51 The minerals that form Earth arose from a variety of physical, chemical, and
52 biological processes over a time span now known to exceed 7 billion years (Hazen et al.
53 2008; Heck et al. 2020). Identifying and systematizing these mineral-forming processes is
54 key to understanding planetary evolution through deep time. Accordingly, we have
55 conducted a comprehensive survey of the modes of formation (i.e., “paragenetic modes”
56 – see below) of 5659 mineral species approved by the International Mineralogical
57 Association’s Commission on New Minerals, Nomenclature and Classification (IMA-
58 CNMNC). The underlying motivation for this effort is to understand how the diversity
59 and distribution of minerals have changed through deep time and to propose a system of
60 mineral classification complementary to IMA-CNMNC protocols that reflects mineral
61 origins in the context of evolving terrestrial worlds.

62 Hazen, Morrison, and colleagues have introduced an “evolutionary system of
63 mineralogy,” which classifies “historical natural kinds” (Boyd 1991, 1999; Hawley and
64 Bird 2011; Magnus 2012; Khalidi 2013; Ereshevsky 2014; Godman 2019; Cleland et al.
65 2021) based on modes of mineral formation, as manifested in their distinctive
66 combinations of physical and chemical attributes (Hazen 2019; Hazen and Morrison
67 2020, 2021; Morrison and Hazen 2020, 2021; Hazen et al. 2021). In this effort, we adopt
68 the principle that any alternative system of mineral classification should complement and
69 amplify IMA-CNMNC protocols (Hatert et al. 2021; Hazen 2021), as they are based on
70 the rigorous time- and origin-independent attributes of idealized chemical compositions
71 and crystal structures (e.g., Burke 2006; Mills et al. 2009; Schertl et al. 2018; Cleland et
72 al. 2021).

73 The alternative evolutionary approach to mineral classification relies on identifying
74 diagnostic suites of mineral properties and the inferred historical processes by which
75 those distinctive properties arose. Accordingly, it is important to enumerate the variety of
76 mineral paragenetic modes, as well as the temporal context of those diverse mechanisms
77 of formation. The principal objective of this contribution is to identify and catalog the
78 paragenetic modes of all known minerals and to attempt to place those mineral-forming
79 mechanisms in the chronological context of Earth's 4.567-billion-year evolution.

80

81 **What is a paragenetic mode?**

82 The term “paragenesis” has been applied in different ways to minerals and their
83 formation. Paragenesis is often used in the context of a specific mineral assemblage: “A
84 characteristic association or occurrence of minerals or a mineral assemblage, especially in
85 ore deposits, connoting a specific equilibrium assemblage or contemporaneous
86 formation” (<https://mindat.org>, accessed 26 June 2021). “Paragenesis” or “paragenetic
87 sequence” is also commonly used to mean the sequence of mineral formation in a suite of
88 rocks, such as a regional metamorphic terrain with a range of temperature-pressure
89 conditions or an ore deposit with stages of mineralization (e.g., Craig and Vaughan 1994;
90 Guilbert and Park 2007). And, in a broader context, paragenesis “may be applied to any
91 sequence or assemblage of minerals related by common formation conditions” (Ebel and
92 Kamilli 2018).

93 Our definition of “paragenetic mode” is most closely related to the latter sense of the
94 term. We define a “mineral paragenetic mode” as *a natural process by which a collection*
95 *of atoms in solid and/or fluid form are reconfigured into one or more new solid forms.*

96 This definition emphasizes an individual mineral’s mode of formation rather than a
97 mineral assemblage or a sequence of mineralization. Consequently, paragenetic modes
98 encompass a wide variety of mineral formation processes, including the formation of
99 primary phases by condensation from a gas; the crystallization of minerals through
100 evaporation of an aqueous solution; the transformation of preexisting phases by lightning,
101 impacts, or other sudden events; and biomineralization.

102 In its broadest sense, our definition of paragenetic mode applies to processes that form
103 a range of solids that are not usually incorporated in IMA-CNMNC protocols, including
104 volcanic glass, kerogen, amber, and other amorphous and/or biologically-formed phases.
105 Note that sharp boundaries do not always exist between natural crystalline compounds
106 and other solid phases; for example, we are still grappling with how to incorporate
107 biological crystal/organic composite materials of the Phanerozoic Eon, such as bones,
108 teeth, and shells.

109 Our definition of paragenetic modes implicitly requires knowledge of three aspects of
110 the mineral-forming process.

111 (1) The initial state of the system: Minerals form from precursor chemical systems at a
112 wide range of initial pressure-temperature-composition (*P-T-X*) conditions. It is
113 often useful to define minerals that emerge through condensation or precipitation
114 from a gas, liquid, or supercritical fluid as “primary minerals,” whereas phases that
115 arise through modification of preexisting minerals (the majority of species) are
116 called “secondary minerals.” Note, however, that intermediate formation processes
117 may occur and the distinction between primary and secondary is not always
118 unambiguous (e.g., Hazen and Morrison 2021).

119 (2) The mechanism of transformation: Mineral-forming mechanisms range from rapid
120 energetic events, such as bolide impacts and lightning strikes with durations on the
121 order of seconds or less, to much more gradual processes, such as solid-state
122 reactions that occur during regional metamorphism or fluid-rock interactions
123 associated with metasomatism. These mechanisms also operate at diverse spatial
124 scales from micrometers (e.g., microbial biomineralization) to hundreds of
125 kilometers (regional metamorphism).

126 (3) The resulting solid phases: Each combination of initial state and transformation
127 mechanism yields one or more mineral phases.

128 These three characteristics of the paragenesis of every mineral – initial state,
129 transformation mechanism, and final state – are reflected in typical descriptions of
130 mineral occurrences, notably in the *Handbook of Mineralogy* (Anthony et al. 1990-2003)
131 and *Rock-Forming Minerals* (Deer et al. 1982-2013). For example, periclase (MgO) is “a
132 relatively high temperature mineral, resulting from the metamorphism of dolomites and
133 magnesian limestones” (Bowles et al. 2011), whereas malachite [Cu₂(CO₃)(OH)₂] is “a
134 common secondary mineral formed in the oxidation zone of copper deposits” (Anthony et
135 al 2003).

136

137 **Uncertainties related to the classification and timing of paragenetic modes**

138 In attempting to classify the paragenetic modes of minerals, we have adopted four
139 general principles:

- 140 1. Every mineral species approved by the IMA-CNMNC must be associated with at
141 least one paragenetic mode (e.g., the copper arsenate mineral popovite forms by
142 sublimation at volcanic fumaroles).
- 143 2. Each paragenetic mode applies to a group of minerals that share a formation
144 process (e.g., more than 400 minerals form by sublimation at volcanic fumaroles).
- 145 3. Mineral-forming environments that represent continuous variations of temperature
146 and pressure, for example regional metamorphic facies (greenschist and
147 amphibolite) or hydrothermal zones (epithermal and mesothermal) have been
148 lumped together.
- 149 4. Related mineral-forming environments that represent an evolutionary sequence
150 have been split; for example, ultramafic igneous rocks are distinguished from
151 mafic igneous rocks that often arise by decompression melting of ultramafic rocks.

152 In spite of these guidelines, our preliminary chronological tabulations of the
153 paragenetic modes of minerals (Table 1; Supplementary Database 1) are subjective in at
154 least two important respects related to: (1) the classification of paragenetic modes, and
155 (2) the relative timing of the initiation of Earth's principal mineral-forming processes.
156 Consequently, enumerating and defining different paragenetic modes must be an ongoing
157 process that involves a broad spectrum of mineralogists and petrologists. In this context,
158 we welcome advice and discussions regarding our provisional classification of
159 paragenetic modes.

160
161 *The classification of paragenetic modes:* A significant source of subjectivity in our study
162 is intrinsic to any classification system – to what extent does one lump or split the varied
163 paragenetic modes of minerals? At the broadest scale, descriptors such as “intrusive

164 igneous,” “regional metamorphic,” and “hydrothermal alteration” are commonly
165 associated with the formation of minerals in different environments. These and similar
166 general terms may be applied to the characterization of paragenetic modes of most
167 minerals (e.g., Philpotts and Ague 2009; Wenk and Bulakh 2016). However, any attempt
168 to further subdivide mineral formation mechanisms, for example into compositional
169 categories of intrusive igneous rocks, facies of regional metamorphism, or gradations of
170 aqueous mineral alteration among metasomatic, hydrothermal, authigenic, and near-
171 surface weathering processes, will be inherently subjective because minerals form over
172 continuous *P-T-X* regimes.

173 Three prior efforts that detail systems of paragenetic modes for important subsets of
174 minerals exemplify the utility and diversity of specialized approaches that can be
175 developed. Guilbert and Park (2007) presented a “litho-tectonic” classification that
176 recognizes more than 100 paragenetic categories of ore deposits based on a hierarchy of
177 (1) tectonic setting (e.g., mid-ocean ridge; cratonic; convergent margin), (2) host
178 lithologies (granite; massive sulfide; skarn), and (3) commodities (copper-gold; coal;
179 chromite). In their system, Guilbert and Park differentiate hydrothermal “Cyprus-type”
180 sulfide deposits from those at mid-ocean ridges, “proximal” massive sulfide deposits
181 from those at subducting margins, and sulfide deposits at back-arc basins versus those
182 from cratons. This detailed and comprehensive system is undoubtedly useful for placing
183 ore deposits in their plate tectonics contexts. However, it is not as appropriate for
184 applications to the full sweep of Earth’s evolution for at least three reasons. First,
185 Guilbert and Park subdivide some types of mineralization, including volcanogenic
186 massive sulfide deposits, iron formations, and carbonatites, into multiple tectonic

187 contexts (e.g., cratons, back-arc basins, or subducting margins) – divisions that only
188 apply to Earth after the initiation of plate tectonics. By contrast, we differentiate
189 paragenetic modes primarily based on pressure-temperature-composition regimes, as
190 opposed to tectonic settings. Second, they narrowly subdivide many deposit types into
191 compositional groups (e.g., Cu, Cu-Mo, Mo, and Cu-Au porphyry copper deposits are
192 listed separately), whereas we do not employ composition as extensively to distinguish
193 among deposit types. And third, numerous non-commercial paragenetic modes, including
194 pre-terrestrial nebular minerals, products of near-surface weathering, impact
195 metamorphism, and biomineralization, are understandably not included in the Guilbert
196 and Park (2007) economic classification.

197 Another specialized list of paragenetic modes was offered in the comprehensive
198 survey of meteorite minerals by Rubin and Ma (2021, their chapter 10). They catalog 22
199 paragenetic modes representing minerals from the full range of meteorite finds and falls,
200 including eight processes related to primary crystallization from gases or melts of
201 different compositions, six variants of aqueous and/or thermal secondary alteration, four
202 variants of solid-state exsolution, shock metamorphism, annealing of amorphous
203 materials, and two forms of meteorite weathering (space weathering versus terrestrial
204 alteration). This revealing list is illuminating in terms of the variety of processes that
205 might produce new solid phases; however, in many instances the exact process by which
206 a meteorite mineral formed is ambiguous and a matter of debate, at times because
207 multiple mechanisms may come into play simultaneously or sequentially. We consolidate
208 Rubin and Ma's 22 modes into seven subsets that we apply specifically to meteorite
209 minerals: condensation of refractory phases in stellar atmospheres; condensation of

210 molecular solids in interstellar environments; condensation from nebular gas;
211 crystallization from chondrule melts; primary minerals formed during asteroid
212 differentiation; thermal, aqueous, and impact alteration of prior meteorite phases in an
213 asteroid body; and terrestrial weathering.

214 A third specialized tabulation of mineral-forming processes was provided by Hill and
215 Forti (1997), who illustrate more than 20 paragenetic modes associated with cave
216 minerals. Their comprehensive survey of 255 cave mineral species distinguishes
217 formation by varied mineral-precipitating aqueous fluids (e.g., rich in silica, carbonate,
218 sulfate, and/or metals); sublimates from subsurface volcanic fumarole vents; oxidation or
219 reduction of prior minerals; bacterial fixation, for example of Fe or Mn minerals;
220 subsurface evaporation to form halides or carbonates; numerous phosphate, nitrate, and
221 organic minerals related to reactions with guano; and freezing of ice. They also present a
222 division into six types of aqueous depositional environments: flowing water, dripping
223 water, pool water, seeping water, condensation water, and thermal water. Like Hill and
224 Forti (1997), we do not consider “cave minerals” a separate paragenetic mode; rather we
225 lump subsets of these shallow subsurface minerals with minerals formed by analogous
226 subaerial processes. Thus, we include halite formed by evaporation in a dry cave with
227 other evaporite minerals. Similarly, we lump subsurface cave fumarole minerals with
228 those that occur at volcanic vents at the surface.

229 Our preliminary tabulation recognizes 57 paragenetic modes, each assigned a
230 reference number (cited as “[#xx]” in this contribution; see Table 1). This classification of
231 paragenetic modes is admittedly subjective in several respects. In particular, when
232 minerals form over a wide range of pressures, temperatures, compositions, and/or time

233 we have, of necessity, selected somewhat arbitrary subdivisions based on the following
234 criteria:

235 1) Depth of formation: In most instances, we distinguish near-surface mineralization
236 that is presumed to form in direct atmospheric contact, either at the surface or in
237 shallow subsurface settings (e.g., volcanic lavas [#9], fumaroles [#11], hot-spring
238 precipitates [#14], subaerial aqueous alteration [#16], and evaporites [#25]), versus
239 subsurface processes not in atmospheric contact (e.g., intrusive igneous formations
240 [#19], subsurface aqueous alteration [#22], primary hydrothermal vein minerals
241 [#33], and regional metamorphism [#40]). Exceptions include Earth's earliest
242 lithologies (most of which are still being produced today) – ultramafic and mafic
243 igneous rocks – for which we lump intrusive and extrusive lithologies (e.g.,
244 peridotite and komatiite [#7], and basalt and gabbro [#8]).

245 2) Metamorphic facies: Rather than differentiating among all facies of regional
246 metamorphic rocks, we recognize three broad *P-T* trends [e.g., as illustrated by
247 Philpotts and Ague (2009), their figure 16.6]. We lump facies of regional
248 metamorphic rocks (e.g., greenschist, amphibolite, and granulite facies) into one
249 paragenetic mode [#40]. We distinguish those facies from metamorphic rocks
250 formed at relatively high pressure and low temperature, including blueschist,
251 eclogite, and ultrahigh-pressure (UHP) facies [#39]; these lithologies are tied to
252 subduction tectonics and thus may be constrained to post-Archean time intervals of
253 Earth history. Finally, in the case of very low-pressure, high-temperature
254 “pyrometamorphic” minerals (Grapes 2006), we recognize four distinct paragenetic
255 environments, including: (1) thermally metamorphosed xenolith minerals (sanidinite,

256 or sometimes hornfels, facies) in volcanic and hypabyssal rocks [#9]; (2) near-
257 surface minerals altered by regional fires, as exemplified by the distinctive
258 mineralogy of the Hatrurim Formation in the Middle East (Gross 1977; Sokol et al.
259 2019) [#51]; (3) anthropogenic pyrometamorphic minerals formed by coal mine fires
260 [#54]; and (4) slag minerals associated with the smelting of ores [#56]. In the cases
261 of regional and high-pressure metamorphic rocks, our conservative approach could
262 be expanded by further subdivision into multiple facies in a future treatment.

263 3) Igneous lithologies: The classification of igneous rocks is a classic problem with no
264 unique solution. At one extreme, Johannsen (1932–1938) proposed hundreds of rock
265 types based on modest variations in mineralogy, bulk composition, and textures.
266 Significant order to the problem was achieved by the Subcommittee on the
267 Systematics of Igneous Rocks of the International Union of Geological Sciences (the
268 “IUGS classification”: Streckeisen 1976, 1979; Le Bas et al. 1986; Le Bas and
269 Streckeisen 1991), which recognizes approximately 60 igneous rock types, again
270 based on mineralogy, composition, and texture. We adopt a more parsimonious
271 approach, with eight paragenetic modes chosen to reflect diagnostic suites of igneous
272 minerals. Ultramafic igneous rocks such as peridotite, pyroxenite, and komatiite
273 [#7], which are composed primarily of Mg-Fe minerals, represent the earliest near-
274 surface rocks on Earth, though these lithologies still form today. We distinguish
275 ultramafic lithologies from plagioclase-rich mafic igneous rocks such as basalt and
276 gabbro, which are derived primarily from decompression melting of prior ultramafic
277 lithologies [#8]. We list both intrusive granitic igneous rocks [#19] and their acidic
278 volcanic equivalents such as rhyolite and dacite [#20], and we differentiate mineral-

279 rich complex pegmatites of granitic [#34] and agpaitic [#35] rocks. We also
280 recognize mineralogically-distinctive carbonatites and related carbonate-rich igneous
281 rocks [#36], as well as layered igneous formations because of their unusual richness
282 in minerals of platinum group elements (PGE; O'Driscoll and VanTongeren 2017)
283 [#37]. Five additional paragenetic modes are closely related to igneous processes:
284 pyrometamorphosed xenoliths in lava [#9], basalt-hosted zeolite minerals [#10],
285 volcanic fumarole minerals [#11] and [#45], and the highly-altered ultramafic rocks
286 of obducted ophiolites [#38]. Note that we do not treat a number of important
287 igneous lithologies, including andesite, anorthosite, monzonite, and syenite
288 (Streckeisen 1976; Le Bas and Streckeisen 1991; Ashwal 1993; Philpotts and Ague
289 2009), as separate paragenetic modes because they do not appear to incorporate new
290 mineral species or distinct formation mechanisms.

291 4) Water-rock interactions: Mineral formation processes related to water-rock
292 interactions pose a significant challenge in classifying mineral paragenetic modes. A
293 number of potentially ambiguous and partially overlapping terms, including aqueous
294 alteration, authigenesis, diagenesis, hydrothermal mineralization, metasomatism, and
295 serpentinization, have been applied to these formation environments of minerals
296 (Heinrich and Henley 1989; Pirajno 2009; Steele-MacInnis and Manning 2020). We
297 are not able to fully resolve this difficulty, but we have adopted the following
298 definitions:

299 • Authigenesis: Authigenesis refers to mineral formation *in situ* by direct
300 precipitation from an aqueous solution, for example as a carbonate cement in
301 detrital sediments. We apply this term exclusively to low- T ($< \sim 100$ °C)

302 sedimentary environments, in contrast to some prior uses in metamorphic
303 petrology. We distinguish marine authigenesis [#17], which must have
304 commenced early in the Hadean Eon, from authigenesis in terrestrial sediments
305 [#24].

306 • Diagenesis: Diagenesis refers to the alteration of sediments in an aqueous
307 environment by increasing T and P , resulting in compaction, lithification,
308 dissolution/precipitation reactions, and some alteration of mineral chemistry by
309 interactions with fluids. Our tabulations do not include diagenesis as a separate
310 paragenetic process, as it may be viewed as the initial stages of metamorphism
311 prior to the formation of new mineral assemblages.

312 • Hydrothermal mineralization: We define hydrothermal mineralization as any
313 precipitation of minerals from an aqueous phase that is > 100 °C or, in the case
314 of near-surface waters, significantly above ambient temperature. We
315 distinguish among mineralization associated with near-surface hot and/or
316 subaerial boiling fluids such as hot springs and geysers [#14]; seafloor
317 hydrothermal vents, known as black smokers and white smokers [#15]; and
318 subsurface mineralization, usually deposited in veins and other fracture
319 systems [#12] and [#33]. Hydrothermal minerals are typically compositionally
320 distinct from their host lithologies. Note that we do not differentiate among
321 different P - T regimes of subsurface hydrothermal mineralization (e.g.,
322 epithermal, mesothermal, and hypothermal).

323 • Metasomatism: Metasomatism is a general term for the subsurface
324 hydrothermal alteration of minerals through mass transfer in an open system

325 (Harlov and Austrheim 2013). As such, the term can be applied to varied
326 chemical processes (e.g., hydration/dehydration, dissolution/precipitation, and
327 ion exchange reactions). Metasomatism may affect the full spectrum of
328 subsurface lithologic settings, including metamorphism and diagenesis of
329 sediments, alteration of plutonic and volcanic rocks, skarn formation, and
330 alteration of a wide variety of ore deposits. Given this broad umbrella of
331 processes and environments, “metasomatism” is not particularly helpful as a
332 paragenetic descriptor. Therefore, we employ it in only in the specific case of
333 “mantle metasomatism” (Luth 2003; O’Reilly and Griffin 2012), which is a
334 term well embedded in the literature related to the alteration of mantle
335 lithologies by complex C-O-H fluids [#41].

- 336 • Serpentinization: Serpentinization is the low- T (typically < 100 °C, but at times
337 to $T > 200$ °C) aqueous alteration process by which anhydrous ferromagnesian
338 minerals in mafic and ultramafic rocks are transformed to hydrous phases,
339 including serpentine polytypes and brucite (Shrenk et al. 2013).
340 Serpentinization is just one of many mineral-producing water-rock
341 interactions; however, it is possibly the most ubiquitous chemical reaction on
342 wet terrestrial planets (e.g., Holm et al. 2015), and it has transformed at least
343 70 % of Earth’s crust throughout its 4.5-billion-year history [#13].
- 344 • Aqueous alteration: “Aqueous alteration” is the most general term for any
345 process that changes minerals by interactions with a water-based solution,
346 irrespective of P - T - X conditions. We adopt “aqueous alteration” as a fallback
347 term for the paragenesis of hundreds of mineral species that do not clearly fit

348 one of the above categories of water-rock interaction, especially when reported
349 details of formation processes are vague. We recognize five subsets of low- T
350 (< 100 °C) aqueous alteration, based on age and depth of formation: subsurface
351 and subaerial aqueous alteration of Hadean lithologies (> 4 Ga) [#16];
352 subsurface aqueous alteration, prior to the Great Oxidation Event (GOE, >2.5
353 Ga) [#22]; subaerial aqueous alteration, pre-GOE [#23]; subsurface aqueous
354 alteration, post-GOE (< 2.5 Ga) [#46]; and subaerial aqueous alteration, post-
355 GOE [#47].

356 In addition to the above paragenetic mechanisms, we recognize five near-surface
357 processes related to water-rock interactions that produce distinctive suites of minerals:
358 freezing of aqueous solutions [#18]; pre-biotic surface precipitation of carbonate,
359 phosphate, and iron formations [#21]; evaporite minerals [#25]; seafloor manganese
360 nodules [#42]; and leaching zone soil minerals, including laterites and bauxites [#48].

361 5) Composition: The lumping and splitting of compositional variants is an admittedly
362 subjective aspect of our proposed system. For example, we distinguish between
363 minerals formed in complex granite pegmatites [#34] versus agpaite pegmatites
364 [#35], because the compositions of their host lithologies (and the resulting mineral
365 species) are dramatically different, even though the mechanisms of mineral
366 formation are similar. We divide contact metamorphic deposits into two somewhat
367 overlapping compositional groups: 356 metamorphosed carbonate (i.e., skarn),
368 phosphate, and iron-formation minerals [#31], are treated as distinct from 412 phases
369 associated with mineral-rich metamorphic Ba, Mn, Pb, and/or Zn deposits [#32].
370 Also, as noted above, we separate 129 hydrothermal sulfides with common transition

371 metals [#12] from most other chalcogenides [#33] on the basis of their assumed
372 chronology. However, with the exception of distinct platinum groups element (PGE)
373 enrichments in layered intrusions [#37], we do not further subdivide hydrothermal
374 metal deposits according to their principal metals or lithologic context.

375 6) Chronology – crust formation: In several instances, we have split minerals derived
376 from mafic/ultramafic lithologies, and thus assumed to have first appeared early in
377 the Hadean Eon (*Stage 3* of Table 1), from minerals likely derived from subsequent
378 granitic lithologies and the formation of continental crust (*Stage 4*) and/or after the
379 GOE (*Stage 7*). Thus, we distinguish minerals formed by authigenesis in marine
380 sediments as early as the Hadean Eon [#17] from authigenic minerals of Earth's
381 earliest continental crust, which likely appeared later [#24]. Similarly, we
382 differentiate the presumed earliest suites of Hadean minerals formed by subaerial
383 aqueous alteration of basaltic crust [#16] from those that more likely first formed
384 subsequently in granitic crust [#23] or after the GOE (see below) [#47]. We also split
385 (with significant uncertainties) some presumably ancient hydrothermal vein sulfides
386 [#12] versus other chalcogenides [#33], because the extensive development of
387 sulfide deposits appears to predate that of other much less abundant chalcogenides,
388 such as those dominant in As, Sb, Se, and Te. Note that in all of these examples,
389 minerals that first formed early in the Hadean Eon continue to form today; our
390 sequence of mineral paragenetic modes thus reflects a gradual accumulation of more
391 and more mineral-forming processes, rather than a sequential replacement of
392 processes.

393 7) Chronology – the Great Oxidation Event: Late Archean (< 3 Ga) atmospheric
394 oxygenation (the “Great Oxidation Event” or GOE) represents a major transition in
395 the formation of near-surface minerals on Earth. Therefore, in four instances we
396 distinguish suites of relatively reduced, near-surface/subaerial phases, presumably
397 formed prior to the GOE from suites of more oxidized minerals that most likely
398 formed after the GOE. We split fumarolic minerals into more reduced phases [#11],
399 such as sulfides that were likely associated with volcanism early in the Hadean Eon,
400 and more oxidized species such as sulfates and arsenates [#45], that presumably
401 formed after atmospheric oxygenation. We differentiate between low-temperature,
402 subsurface aqueous alteration prior to the GOE [#22] and post-GOE [#46]. Similarly,
403 we divide low-temperature, subaerial aqueous alteration pre-GOE [#23] and post-
404 GOE phases [#47]. We also enumerate 11 minerals formed by anaerobic microbial
405 metabolism prior to the GOE [#44], compared to 77 biominerals produced directly
406 through cellular processes post-GOE [#49].

407 8) Near-surface oxidation/weathering: Because of the large number (~ 2000 species) of
408 secondary minerals formed by near-surface oxidation, weathering, and hydration
409 [#47], we have divided these diverse phases into nine subgroups designated [#47a] to
410 [#47i] based on mineral chemistry (thus they *are not* additional paragenetic modes).
411 Most post-GOE weathered phases fall into two or more of these compositional
412 subgroups. For example, the rare mineral blue lizardite $[\text{Na}_7(\text{U}^{6+}\text{O}_2)(\text{SO}_4)_4\text{Cl}\cdot 2\text{H}_2\text{O}]$
413 is included in four compositional subcategories: near-surface hydration [#47a],
414 sulfates [#47b], uranyl (U^{6+}) minerals [#47f], and halogen-bearing phases [#47g].

415

416 *The relative timing of Earth's principal mineral-forming processes:* An important
417 objective of our study is to present a chronological tabulation of modes of mineral
418 formation, with quantitative geochronological constraints where possible. However, this
419 effort is faced with significant uncertainties. In a few instances, for example with primary
420 meteorite minerals [#1] to [#5] (> 4.56 Ga); Phanerozoic biomineralization and
421 taphonomic minerals (i.e., minerals formed via decay/alteration of biological materials)
422 [#49], [#52], and [#53] (< 541 Ma); coal minerals [#50] (< 360 Ma); and anthropogenic
423 minerals [#54] to [#57] (< 10 Ka), the ages of minerals are well defined by the nature of
424 the processes in question. In addition, over the past decade we have developed the
425 Mineral Evolution Database (MED; <https://rruff.info/evolution>, accessed 17 March 2021;
426 Golden et al. 2016; Golden 2020), with more than 190,000 minerals species/age/locality
427 data for more than 1000 different mineral species. However, in the cases of most mineral
428 species and their formation mechanisms, the absolute and relative timings of paragenetic
429 modes are poorly constrained.

430 Two well-known factors contribute to these uncertainties. First is the paucity of any
431 geological formations older than ~3.5 Ga; therefore, solid evidence for the formation and
432 timing of Hadean and Paleoarchean minerals is literally all but lacking. The ages of many
433 mineral-forming processes might be inferred if we knew the timings of significant
434 episodes in Earth history, such as the formation of continents, the establishment of
435 oceans, and the transition from vertical plume tectonics to lateral plate tectonics.
436 However, the nature and timing of these and other events from Earth's first billion years
437 are matters of intense ongoing debates. Among the uncertainties are:

- 438 • The composition and extent of Earth’s earliest crust: The mineral evolution of
439 differentiated Earth began with subaerial solidification of the magma ocean that
440 formed immediately after the Moon-forming impact (> 4.50 Ga; Barboni et al. 2017;
441 Thiemans et al. 2019), coupled with initiation of mantle convection, possibly under a
442 “stagnant lid” (i.e., prior to significant recycling of surface layers; e.g., Debaille et al.
443 2013; Piper 2013; Stern 2018; Korenaga 2021). General agreement exists that
444 Earth’s earliest crust featured globe-spanning mafic/ultramafic igneous lithologies;
445 however, significant debate remains regarding that crust’s composition and thickness
446 – parameters that may have strongly influenced the earliest stages of mineral
447 evolution (Rollinson 2007b; Korenaga 2021). The earliest crust was likely more
448 mafic (i.e., with a higher average Mg content) than today (Taylor and McLennan
449 1995; Kemp and Hawksworth 2003; Keller and Schoene 2012). If a relatively thick
450 mafic crust (i.e., similar in composition to modern oceanic crust) prevailed, then a
451 gradual tectonic transition from stagnant lid to subduction seems plausible. If, on the
452 other hand, Earth’s first crust was dominated by a relatively thin ultramafic layer, as
453 advocated by Korenaga (2021), then sinking dense crustal slabs may have triggered
454 an active early style of subduction-driven plate tectonics in the Hadean Eon. In this
455 study, we assume that some combination of mafic and ultramafic crustal lithologies
456 dominated Earth’s earliest mineral diversity by ~4.50 Ga, without adopting a
457 position on the compositional and tectonic details.
- 458 • The composition and extent of Earth’s earliest oceans: Most models of early Earth
459 posit the rapid evolution of a hydrosphere, culminating in globe-spanning oceans by
460 4.45 Ga (Wilde et al. 2001; Mojzsis et al. 2001; Elkins-Tanton 2011). Anoxic

461 Hadean oceans must have differed significantly from more recent marine
462 environments. For example, estimates of Hadean ocean chemistry suggest
463 significantly higher salinity than the modern oceans (Holland 1984; Knauth 2005;
464 Marty et al. 2018) – conditions that might have led to enhanced evaporite deposition
465 at coastal margins. In this study, we assume that oceans were well established by
466 4.45 Ga.

467 • The timing and extent of continental crust formation: A major uncertainty is the
468 timing of initiation and evolution of buoyant, felsic continental crust that was
469 relatively enriched in incompatible elements – a significant source of mineral
470 diversity. Stable, long-lived continental crust is thought to form principally through
471 extensive partial melting of a hydrated mafic layer in the upper mantle. Virtually all
472 models posit formation of some felsic crust by 4.4 Ga, but estimates of the rate of
473 subsequent continental “net crustal growth” vary wildly. At one extreme, some
474 authors suggest rapid granitic production, achieving close to modern extent of
475 continental crust by the early Hadean Eon (Armstrong 1991; Rosas and Korenaga
476 2018; Guo and Korenaga 2020). Others argue for a more gradual development of net
477 crustal volume, with modern levels not achieved until the mid-Proterozoic or later
478 (Belousova et al. 2010; Dhuime et al. 2012; Greber et al. 2017; see Korenaga 2018,
479 his Figure 1 and references therein). In this study, we assume that felsic continental
480 crust sufficient to enhance Earth’s mineral diversity developed by 4.40 Ga, without
481 weighing in on the debate regarding the rate of continental evolution.

482 • The extent of dry land: Significant uncertainties exist regarding the volume and
483 depth of Hadean surface waters. Notably, recent models suggest that the Hadean

484 ocean may have held significantly more water, perhaps twice today's volume
485 (Kurokawa et al. 2018; Dong et al. 2021), as a consequence of the relatively hot, and
486 therefore dry, peridotitic mantle prior to 4 Ga. Subsequent mantle hydration through
487 plate tectonics gradually decreased the ocean's volume to modern levels (Jarrad
488 2003; Korenaga 2008; Korenaga et al. 2017; Rosas and Korenaga 2021). A
489 voluminous early ocean, possibly coupled with less extreme topography owing to a
490 steeper geothermal gradient and/or lack of orogenesis (e.g., Tang et al. 2021), may
491 have resulted in a largely submerged Hadean world with extensive serpentinization
492 and other water-rock interactions (Voosen 2021, Korenaga 2021). Such a scenario
493 has important implications for the emergence of dry land, which played a number of
494 roles in mineral diversification, for example through the formation of minerals by
495 evaporation, volcanic fumaroles, hot springs and geysers, photo-oxidation, lightning
496 strikes, and impact mineralization. In spite of uncertainties regarding the extent of
497 dry land, we assume that at least some subaerial continental crust has been present
498 continuously since ~4.4 Ga.

499 • The nature of Earth's earliest atmosphere: That Earth's atmospheric composition has
500 changed dramatically through time is certain. However, the nature and timing of
501 those changes is another enigmatic aspect of early Earth that influences models of
502 Hadean mineral evolution. The widely cited model of Zahnle and colleagues (Zahnle
503 2006; Zahnle et al. 2007) suggests a Hadean transition from an initially dense CO₂-
504 rich atmosphere to one dominated by N₂ – a change that must have been
505 accompanied by extensive early deposition of carbonate minerals. We adopt this

506 scenario and assume that carbonate precipitation was an important paragenetic
507 process throughout the Hadean Eon.

508 • The nature and timing of the commencement of plate tectonics: The initiation of
509 subduction, possibly tied to a transition from vertical (plume-dominated or “heat
510 pipe”) tectonics to modern-style lateral tectonics (Van Kranendonk et al. 2004,
511 2007a; Moore and Webb 2013), dramatically expanded Earth’s mineralogical
512 repertoire. However, significant uncertainties are reflected in a range of competing
513 models regarding both the style and timing of extensive crustal recycling (Condie
514 and Pease 2008; Brown et al. 2020; Korenaga 2021). Estimates for the initiation of
515 plate tectonics range from > 4 Ga (Hopkins et al. 2008; Rosas and Korenaga 2018;
516 Turner et al. 2020) to < 1 Ga (Stern 2005, 2018; Rollinson 2007a), with additional
517 discussions related to continuous versus episodic processes (O’Neill et al. 2007;
518 Belousova et al. 2010; Moyen and van Hunen 2012). In spite of these varied ideas,
519 many researchers have concluded that a significant transition occurred near ~3 Ga to
520 a “modern style” plate tectonics, exemplified by the Wilson cycle (Shirey and
521 Richardson 2011; Dhuime et al. 2012; van Hunen and Moyen 2012; Tang et al.
522 2016; Cawood et al. 2018). In this study we assume that significant subduction-
523 driven plate tectonics and associated mineral-forming processes began at some point
524 after the earliest appearance of oceans and continental crust (i.e., < 4.3 Ga), but
525 significantly before atmospheric oxygenation (> 3.0 Ga).

526 In conclusion, we assume the following sequence of mineral-forming processes
527 associated with the evolution of Earth’s lithosphere and hydrosphere: (1) solidification of
528 a mafic/ultramafic crust (*Stage 3a*; > 4.50 Ga); (2) formation of oceans and an active

529 hydrosphere (*Stage 3b*; > 4.45 Ga); (3) continental crust formation (*Stage 4*; > 4.40 Ga);
530 and (4) initiation of subduction-driven plate tectonics (*Stage 5*; < 4.3 Ga). Note that this
531 timeline is significantly more compressed than originally proposed by Hazen et al.
532 (2008), thus suggesting that much of Earth's mineral diversity was established within the
533 first 250 million years.

534

535 *Preservation bias*: A critical factor impeding our understanding of the relative timing of
536 paragenetic modes relates to inevitable biases associated with limited preservation of
537 Archean and Proterozoic rocks, especially near-surface minerals associated with
538 evaporites, fumaroles, hot springs, and other transient environments (e.g., Liu et al.
539 2019). Most minerals from those sources have been preferentially lost – preservation
540 biases that are especially relevant to documenting the first appearance of many rare
541 minerals (Hazen and Ausubel 2016). Therefore, the absolute and relative timing of
542 Earth's earliest minerals must often be inferred from geochemical and geophysical
543 models.

544 Significant uncertainties in the timing of mineral paragenesis relate to the emergence
545 of minerals incorporating rare elements. In particular, 41 relatively rare mineral-forming
546 elements (defined here as present at < 5 ppm in Earth's crust), including Sb, As, Be, Bi,
547 Br, Cd, Cs, Au, Hf, In, Hg, Mo, Se, Ag, Ta, Te, Tl, Sn, U, W, the platinum group
548 elements, and the rare earth elements, account for almost 2400 mineral species. Thus,
549 fewer than 1 in 10,000 crustal atoms play an essential role in more than 42 % of Earth's
550 total mineral diversity (<https://rruff.info/ima>, accessed 7 March 2021). An unanswered

551 question is how much time is required for these scarce elements to achieve localized
552 concentrations sufficient to produce new minerals.

553 Some evidence points to time periods greater than a billion years, as exemplified by
554 the earliest known minerals containing Be (Grew and Hazen 2014), Cs (London 2008),
555 and Hg (Hazen et al. 2012) from 3.00, 2.65, and 3.04 Ga, respectively. The paucity of
556 these and other minerals containing rare elements with ages greater than 3 Ga suggests
557 that it takes hundreds of millions of years for some scarce elements to become
558 sufficiently concentrated, perhaps through fluid-rock interactions in large volumes of
559 crust and upper mantle rocks affected by subduction-generated fluids.

560 On the other hand, at least some minerals incorporating rare elements arose much
561 earlier in highly localized deposits, many of which did not survive or are yet to be
562 exhumed. For example, micrometer-scale “nuggets” of PGE alloys enriched in osmium
563 and ruthenium have been found in meteorites, formed > 4.55 Ga either as primary
564 condensates from the solar nebula (Morrison and Hazen 2020) or exsolved from
565 thermally metamorphosed Fe-Ni metal of differentiated planetesimals and preserved in
566 iron meteorites (Hazen and Morrison 2021). Thus, in spite of the presence of Os and Ru
567 at crustal concentrations of 1 part per billion or less, these platinum group elements
568 rapidly segregated into concentrations sufficient to form PGE minerals. We conclude that
569 much more research will be required to determine how rapidly minerals of rare elements
570 might have formed in Earth’s crust.

571

572 **Systematic Survey of Paragenetic Modes**

573 In this section we describe 57 paragenetic modes of minerals, listed in a suggested
574 order of earliest appearance, as summarized in Table 1. This analysis is based on a newly
575 constructed database of 5659 minerals, each represented by one or more paragenetic
576 modes (see Supplementary xlsx spreadsheet, [EDITOR: Please advise here on format]) –
577 work that would not have been possible without the availability of large and growing
578 open-access data resources (Hazen 2014; Lafuente et al. 2015; Hazen et al. 2019; Golden
579 2020; Prabhu et al. 2021). Paragenetic modes for each IMA-CNMNC-approved mineral
580 species were determined by consulting one or more of the following sources: (1) lists of
581 IMA-approved mineral species and associated links to primary references
582 (<https://rruff.info/ima>, accessed 25 February 2021; Lafuente et al. 2015); (2) tabulations
583 of mineral species and their localities, associated species, and (in many instances)
584 geological contexts (<https://mindat.org>, accessed 25 February 2021); (3) detailed
585 descriptions of paragenesis for rock-forming minerals in Deer et al. (1982-2013), *Rock-*
586 *Forming Minerals*, Second Edition, 11 volumes; (4) brief descriptions of “Occurrence” in
587 Anthony et al. (1990-2003), *Handbook of Mineralogy*, 6 volumes; and (5) books and
588 articles describing new individual mineral species and their modes of occurrence from
589 primary references (as listed in sources 1 through 4, above). This initial version of the
590 paragenetic mode spreadsheet, with 10,556 combinations of an IMA-approved mineral
591 species and one of 57 paragenetic modes, represents an ongoing effort; we welcome
592 additions and corrections.

593 Several aspects of this treatment (Table 1) should be noted:

- 594 • While most of the paragenetic modes encompass numerous mineral species, several
595 unusual categories are represented by 10 or fewer minerals. These relatively rare

596 paragenetic processes include minerals formed by interstellar condensation [#2] (8
597 species), near-surface freezing [#18] (4), auto-oxidation through radioactive decay
598 [#27] (9), photo-oxidation [#28] (10), lightning [#29] (9), and shear stresses such as
599 mylonitization [#43] (9).

600 • A significant number of durable mineral species, including metal alloys, carbides,
601 and chalcogenides, are known only from detrital deposits, placers, or heavy mineral
602 separates. In several instances, the origins of these grains are unknown. We list
603 “detrital” as a paragenetic mode, even though detrital refers to a local accumulation
604 of mineral grains in a sedimentary environment, as opposed to a formation
605 mechanism, *per se*.

606 • A number of mineral-forming processes, including exsolution, order-disorder
607 transitions, and reversible phase transitions, occur in the solid-state during cooling
608 and/or annealing. We have chosen to lump these processes with broader igneous and
609 metamorphic paragenetic categories rather than treat them as separate formation
610 processes. However, solid-state transition mechanisms could be added as one or
611 more paragenetic modes in future studies.

612 • Several minerals form only in specific environmental contexts, for example in fluid
613 inclusions [e.g., zabuyeite; $\text{Li}_2(\text{CO}_3)$], in caves [guanine; $\text{C}_5\text{H}_3(\text{NH}_2)\text{N}_4\text{O}$], or as
614 epitaxial overgrowths [marsturite; $\text{NaCaMn}_3\text{Si}_5\text{O}_{14}(\text{OH})$]. We catalog these
615 minerals according to their petrogenetic settings, rather than by their environmental
616 contexts.

617 • Similarly, we do not consider the formation processes of morphologically distinct
618 minerals, such as lava phenocrysts, minerals that occur exclusively as nanophases

619 (e.g., protoenstatite; MgSiO_3), or minerals that display efflorescence, as distinct
620 paragenetic modes.

621 • Finally, we do not list minerals from the Moon or Mars. The comparative mineralogy
622 of extraterrestrial bodies will be treated in a separate contribution.

623

624 Stage 0. Pre-terrestrial “Ur-minerals” We tabulate 296 IMA-approved species as pre-
625 terrestrial minerals on the basis of their occurrences in meteorites (Hazen and Morrison
626 2021; Rubin and Ma 2021). We divide these diverse phases, at least 97 of which are
627 known only from meteorites, into six sequential paragenetic modes ([#1] through [#6]),
628 representing the first three stages of mineral evolution.

629 [#1 – *Stellar atmosphere condensates*]: The earliest of these phases, dubbed “Ur-
630 minerals” by Hazen et al. (2008), include 22 IMA-approved mineral species that formed
631 prior to the solar nebula in the expanding, cooling atmospheres of highly-evolved stars
632 (Zinner 2014; Nittler and Ciesla 2016; Hazen and Morrison 2020). Stellar minerals,
633 which are identified by their extreme isotopic anomalies as pre-solar grains, include the
634 most ancient condensed matter yet identified, with some individual stellar moissanite
635 (SiC) grains dated ~7 billion years old (Heck et al. 2020). Hazen and Morrison (2020)
636 catalogued these stellar minerals and further subdivided them into three probable sources
637 – AGB stars, classic novae, and core-collapse supernovae. Subsequent work by Boujibar
638 et al. (2021) employed cluster analysis on the isotopic attributes of thousands of stellar
639 moissanite grains to identify at least seven distinct SiC groups associated with variants of
640 these stellar types.

641 [#2 – *Interstellar condensates*]: Morrison and Hazen (2020) listed an additional 8
642 probable interstellar condensed molecular C-H-O-N “ice” phases, which have been
643 identified in so-called “cool” ($T < 20$ K), “dense” ($P < 10^{-13}$ atm) molecular clouds by
644 telescopic observations of absorption and emission spectra of interstellar molecules in
645 radio, microwave, or infrared wavelengths (Greenberg 1991; Whittet 2003; Gibb et al.
646 2004). All of these condensed phases would have formed prior to the solar nebula (i.e., >
647 4.567 Ga). With the exception of water ice, these molecular solids are not currently
648 recognized as minerals by the IMA-CNMNC.

649

650 *Stage 1. Primary nebular phases* *Stage 1* of Earth’s mineral evolution, which occurred
651 between 4.567 and 4.561 Ga, encompassed two mineral-forming processes.

652 [#3 – *Solar nebular condensates*]: Initial mineral formation occurred as nebular gas
653 cooled and highly refractory phases condensed at temperatures greater than ~1000 K.
654 Morrison and Hazen (2020) catalogued 48 IMA-approved minerals that are preserved in
655 calcium-aluminum-rich inclusions (CAIs; MacPherson 2014), amoeboid olivine
656 aggregates (AOAs; Krot et al. 2004), and ultra-refractory inclusions (URIs; El Goresy et
657 al. 2002).

658 [#4 – *Primary chondrule phases*]: Overlapping pulses of nebular mineralization are
659 preserved as the primary igneous minerals of chondrules, which represent solidified
660 droplets, typically < 0.1 cm diameter, that formed during the first few million years of the
661 solar nebula, ~4.566 to 4.561 Ga (Brearley & Jones 1998; Krot et al. 2014; Russell et al.
662 2018; Hazen et al. 2021). Chondrules are preserved in abundant chondrite meteorites,
663 which may be thought of as the oldest sedimentary rocks in the solar system. We identify

664 47 primary chondrule minerals, most of which form from 10 abundant chemical elements
665 – C, O, Mg, Al, Si, S, Ca, Ti, Cr, and Fe.

666
667 Stage 2. Planetesimal differentiation Within the first million years of the solar nebula's
668 formation, the primary condensates of *Stage 1* had begun to accrete into the first
669 generation of planetesimals. Over the next few million years (~4.566 to 4.560 Ga;
670 Blichert-Toft et al. 2010), some of these bodies grew to diameters exceeding 100 km –
671 large enough to melt and differentiate into a metallic core and rocky mantle. Subsequent
672 collisions disrupted some of these objects to produce a rich variety of non-chondritic
673 meteorites.

674 [#5 – *Primary asteroid phases*]: Morrison and Hazen (2021) tabulate 94 IMA-
675 approved species that occur as primary igneous minerals in iron, stony-iron, and
676 achondrite meteorites (Mittlefehldt et al. 1998; Krot et al. 2014; Mittlefehldt 2014).

677 [#6 – *Secondary asteroid phases*]: A final pre-terrestrial phase of mineral evolution is
678 preserved as a diverse variety of secondary phases formed by aqueous, thermal, and/or
679 impact alteration of prior meteorite minerals. These processes produced more than 200
680 IMA-approved mineral species, primarily during an interval from ~4.565 to 4.550 Ga
681 (McSween et al. 1988; Brearley and Jones 1998; Mittlefehldt et al. 1998; Hazen and
682 Morrison 2021; Rubin and Ma 2021). This period of secondary mineralization saw the
683 first occurrence of several important mineral groups, including sulfates, carbonates,
684 hydroxides, and layer silicates (notably clay minerals).

685 An important caveat relates to the distinction between primary and secondary
686 meteorite minerals. Most secondary meteorite minerals are unambiguously the products
687 of aqueous and/or thermal alteration of earlier phases, yet at least two complications may

688 arise. First, terrestrial weathering may lead to some secondary alteration that is difficult
689 to distinguish from pre-terrestrial processes. However, most terrestrial weathering
690 products arise from oxidation (see *Stage 7* below) and are thus distinct from asteroidal
691 alteration.

692 A subtler situation arises from the gradual alteration of primary asteroid minerals to
693 secondary phases. Such transformations may involve incremental shifts in composition
694 and atomic structure spanning thousands to millions of years. Some suites of secondary
695 mineral properties, such as exsolution, order/disorder, or zoning, are the consequences of
696 thermal and/or aqueous alteration, but sharp boundaries may not exist between the
697 primary and secondary forms of minerals. Furthermore, it has been suggested that some
698 presumably secondary asteroidal minerals might have also formed via primary nebular
699 processes, for example via sulfidization, oxidation, and/or hydration during pre-
700 accretionary interactions with a warm nebular gas (Krot et al. 1995, their Table 2;
701 Bischoff 1998; Ciesla et al. 2003). These ambiguities are emblematic of challenges to any
702 comprehensive tabulation of mineral paragenesis.

703

704 *Stage 3a. Earth's earliest Hadean crust* Proto-Earth's earliest crust must have solidified
705 before 4.55 Ga, shortly after the planet's accretion and differentiation, though that stage
706 of Earth's mineral evolution is lost. The Moon-forming event (perhaps ~ 4.51 Ga;
707 Barboni et al. 2017) completely obliterated the initial solid outer shell, but a new crust
708 dominated by ultramafic and mafic igneous lithologies crystallized shortly thereafter (>
709 4.50 Ga). No minerals have been preserved from that Hadean world, save for a few
710 detrital zircon (ZrSiO₄) crystals with ages as great as 4.4 Ga (Wilde et al. 2001).

711 Nevertheless, we suggest that five major groups of minerals, totaling approximately 400
712 mineral species, arose from this earliest terrestrial *Stage 3a* of mineral evolution (modes
713 [#7] through [#11]; Table 1). Many of these phases, previously cataloged by Hazen
714 (2013) and Morrison et al. (2018) in inventories of Hadean “paleomineralogy,” are
715 familiar oxides and silicates with the most abundant crustal elements (notably H, Al, Na,
716 Mg, K, Ca, Fe, and Ti), as well as accessory sulfides, possibly arsenides, and other
717 relatively reduced phases.

718 [#7 – *Ultramafic igneous rocks*]: Ultramafic igneous rocks, including peridotite,
719 pyroxenite, and komatiite, are dominated by ferromagnesian minerals and lack significant
720 plagioclase (Dick 1989; Isley and Abbott 1999; Guilbert and Park 2007; Philpotts and
721 Ague 2009; Lambert et al. 2016). These lithologies played a significant role in the
722 mineralogy of Hadean Earth’s crust and mantle (Rollinson 2007b; Van Kranendonk et al.
723 2007b), though significant uncertainty remains regarding the relative volumes of
724 ultramafic versus mafic lithologies (e.g., Korenaga 2021). We list 123 minerals that have
725 been identified in ultramafic intrusive and extrusive igneous rocks.

726 [#8 – *Mafic igneous rocks*]: Mafic igneous rocks, notably volcanic basalt and its
727 intrusive equivalent gabbro, have been important crustal lithologies throughout Earth’s
728 history (Rollinson 2007b; Van Kranendonk et al. 2007b; O’Neil et al. 2008). Most basalt
729 is thought to form by decompression partial melting of ultramafic rocks in Earth’s
730 mantle, which produces a buoyant magma. Not only is basalt the dominant lithology of
731 the oceanic crust, but it also is produced in huge volumes in continental settings during
732 the episodic production of large igneous provinces (LIPS; Ernst 2014), which have
733 occurred since at least 2.8 Ga (Prokoph et al. 2004). The mineralogy of basalt is always

734 dominated by plagioclase and pyroxene; however, a variety of basalt subtypes based on
735 relative amounts of Mg, Fe, Al, Ti, and alkali metals incorporate different accessory
736 minerals and display diagnostic compositional attributes. In this study, we identify 93
737 mineral species from Precambrian mafic igneous rocks. Further detailed studies of basalt
738 minerals, for example employing cluster analysis on trace and minor elements, may point
739 to additional subdivision of these phases into natural kinds (Hazen 2019; Boujibar et al.
740 2021).

741 [#9 – *Lava/xenolith minerals*]: Additional mineralogical variety would have been
742 present in the form of thermally-altered xenoliths that were derived from both mantle and
743 crustal sources in abundant Hadean lavas (Grapes 2006). We identify 127 mineral species
744 that were contributed by this igneous pyrometamorphic (most typically sanidinite facies)
745 process. Note that some of these xenolith minerals, notably those representing altered
746 carbonates and alkalic igneous rocks, must have formed significantly after 4.5 Ga to
747 allow enough time for compositional differentiation.

748 [#10 – *Basalt-hosted zeolite minerals*]: A significant number of late-stage zeolite
749 group minerals likely formed in the cavities of cooling basalt (Deer et al. 2004). We
750 identify more than 100 such phases, with the caveat that unaltered zeolite group minerals
751 are rarely preserved in Precambrian formations and any tabulation based on ages of
752 formation must remain speculative.

753 [#11 – *Volcanic fumarole minerals, reduced*]: A modest suite of a few dozen reduced
754 phases, predominantly transition metal sulfides, likely formed as sublimates at Hadean
755 volcanic fumaroles (Grapes 2006; Vergasova and Filatov 2016). These phases represent a

756 subset of the more than 450 documented fumarole minerals, most of which are more
757 oxidized phases that we assign to post-GOE formation [#45].

758

759 Stage 3b. Earth's earliest hydrosphere Earth's earliest hydrosphere, fueled by
760 ubiquitous volcanic venting of water vapor, led to cloud formation, rain, development of
761 streams and rivers, and ultimately the establishment of oceans. A robust hydrological
762 cycle was probably operating shortly after the solidification of Earth's crust, with
763 substantial bodies of water covering a large fraction of the surface by > 4.45 Ga (Wilde et
764 al. 2001; Elkins-Tanton 2011; Dong et al. 2021), and a vigorous subsurface hydrothermal
765 circulation of aqueous fluids (Heinrich and Henley 1989; Pirajno 2009). The consequent
766 water-rock interactions may have produced as many as 350 mineral phases in near-
767 surface marine and terrestrial environments.

768 [#12 – *Hadean hydrothermal minerals*]: Subsurface Hadean hydrothermal sulfide
769 deposits, with more than 100 likely species, represent an important yet enigmatic early
770 source of mineral diversity. Today, hydrothermal systems boast more than 850 species of
771 sulfides, arsenides, antimonides, and a wide range of sulfosalts bearing relatively rare
772 elements such as Ge, Sn, Bi, Se, and Te. However, we postulate that these uncommon
773 elements were not sufficiently concentrated in Hadean hydrothermal fluids to generate
774 that wide range of compounds. In spite of longstanding interest in the secular variation of
775 sulfide-rich ore bodies (Laznicka 1973; Meyer 1988; Titley 1993; Barnes and Rose 1998;
776 Goldfarb et al. 2001; Groves et al. 2005, 2010; Huston et al. 2010; Leach et al. 2010;
777 Maier and Groves 2011; Jenkin et al. 2015), the changing mineralogies of these deposits
778 through time, especially regarding minerals containing relatively rare elements, have not

779 been detailed to our knowledge. We therefore limit our list of the earliest hydrothermal
780 chalcogenides to sulfides (and in a few cases arsenides) of the commonest transition
781 metal elements, as well as PGE elements, which are thought to concentrate in fluids
782 associated with ultramafic lithologies owing to their highly incompatible nature (Mungall
783 and Naldrett 2008). We list most hydrothermal ore minerals under *Stage 4* [#33], when
784 extensive fluid-rock interactions in the upper mantle and crust associated with subduction
785 is thought to have selected and concentrated rare elements.

786 [#13 – *Hadean serpentinization*]: Low-temperature aqueous alteration of Hadean
787 igneous lithologies, in both near-surface and subaerial environments, must have produced
788 hundreds of new mineral species. Most notably, serpentinization would have transformed
789 ocean floor mafic and ultramafic rocks to familiar assemblages of brucite, serpentine,
790 magnetite, and more than 60 other phases (Blais and Aubrey 1990; Lowell and Rona
791 2002; Palandri and Reed 2004; Shrenk et al. 2013; Holm et al. 2015; Menez et al. 2018).

792 [#14 – *Hot springs, geysers*]: The surface of the Hadean world would have featured
793 abundant subaerial hot springs and geysers that produced a range of geothermal minerals,
794 perhaps including the earliest terrestrial occurrences of calcite (CaCO_3), baryte (BaSO_4),
795 and a variety of hydrated phases. Widespread low-temperature aqueous alteration of
796 Hadean lithologies would also have enriched early Earth's inventory of hydrous silicates,
797 including clay minerals and zeolites (Deer et al. 2004; Wilson 2013).

798 [#15 – *Black/white smokers*]: A subset of more than 20 hydrothermal sulfide minerals
799 would have occurred with high-temperature aqueous alteration phases at Earth's earliest
800 "black smoker" environments, which, along with carbonate-rich "white smokers," we
801 consider to be a distinct seafloor paragenetic environment (Hekinian et al. 1980; Haymon

802 and Kastner 1981; Palandri and Reed 2004; Schwarzenbach and Steele-MacInnis 2020).
803 Note that the abundance and character of submarine hydrothermal vents may have
804 changed significantly through time. Compared to today, Hadean Earth had significantly
805 greater volcanic activity coupled with a larger extent of oceans. Nevertheless, the onset of
806 modern-style plate tectonics would have established continuous chains of submarine
807 vents at and near divergent plate boundaries (Lowell et al. 2008). Therefore, we conclude
808 that seafloor hydrothermal systems have been active mineral-forming environments for at
809 least 4.5 billion years.

810 [*#16 – Low-T aqueous alteration*]: In addition to serpentinization, low-temperature
811 aqueous alteration of Hadean subaerial and shallow subsurface lithologies produced more
812 than 80 mineral species, including dozens of zeolites, clay minerals, and other hydrous
813 silicates (Deer et al. 2004; Wilson 2013).

814 [*#17 – Marine authigenic minerals*]: Hadean seafloor water-rock interactions would
815 have produced a complementary suite of perhaps 50 authigenic phases in low-
816 temperature marine sediments, including a variety of hydrous silicates, notably zeolites
817 (Deer et al. 2004). We have attempted to differentiate authigenic minerals, which
818 precipitated in place (typically in a sedimentary environment), from aqueous processes
819 that alter prior minerals through fluid-rock interactions (e.g., modes [*#16*], [*#22*], [*#23*],
820 [*#46*], and [*#47*]). Note also that we distinguish these marine authigenic minerals, which
821 began forming early in the Hadean Eon, from those that we suggest formed somewhat
822 later in a continental setting [*#24*].

823 [*#18 – Minerals formed by freezing*]: Finally, the Hadean hydrosphere must have
824 hosted the earliest terrestrial examples of minerals formed by freezing of aqueous

825 solutions, most abundantly ice (H₂O), but also rare occurrences of hydrohalite
826 (NaCl·2H₂O), ikaite (CaCO₃·6H₂O), and possibly ernstburkeite [Mg(CH₃SO₃)₂·12H₂O],
827 which was discovered in an ice core from Antarctica (Genceli Güner et al. 2013).

828

829 Stage 4a. Earth's earliest continental crust The occurrence of individual zircon grains
830 with ages as great as ~4.4 Ga (Wilde et al. 2001; Cawood et al. 2013) suggests that some
831 granitic continental crust formed through partial melting of hydrated basalt within Earth's
832 first 150 million years, significantly before the onset of modern-style plate tectonics
833 according to many models (Shirey and Richardson 2011; Dhuime et al. 2012; van Hunen
834 and Moyen 2012; Tang et al. 2016; Johnson et al. 2017; Cawood et al. 2018; however,
835 see Korenaga 2021). Crustal processes during the Hadean and Archean Eons led to
836 significant mineral diversification, ultimately approaching a total of 2400 mineral species
837 (Table 1).

838 [#19 – *Granitic intrusive rocks*]: We list 143 primary minerals that were associated
839 with the formation of granite and related intrusive acidic rocks during the Hadean Eon –
840 mineralization that continues today. Studies of many granitic bodies point to different
841 sources of parent magmas, including mantle-derived (“M” type); sediment-derived (“S”
842 type); deep-crustal, orogenic igneous (“I” type); and anorogenic (“A” type) granites
843 associated with hot spots (Chappell and White 2001; Eiler 2007; Philpotts and Ague
844 2009). Therefore, an intriguing aspect of granite mineralogy, yet to be explored, is
845 whether different types of granite might result in distinctive mineral attributes and thus
846 warrant further paragenetic subdivisions.

847 [#20 – *Acidic volcanic rocks*]: Rhyolite, dacite, and other quartz- and alkali feldspar-
848 bearing volcanic rocks played an important role in the evolution of continental crust
849 (Rollinson 2007b; Van Kranendonk et al. 2007b; Philpotts and Ague 2009). We identify
850 45 mineral species produced by acidic volcanism, including phases uniquely associated
851 with ash, such as quadridavyne [(Na,K)₆Cl₂Ca₂Cl₂(Si₆Al₆O₂₄)], as well as its rapid
852 devitrification and hydration products [e.g., clinoptilolite-Na; Na₆(Si₃₀Al₆)O₇₂·20H₂O].
853 Note that we distinguish intrusive and extrusive acidic rocks because they have different
854 suites of minerals, as opposed to ultramafic [#7] and mafic [#8] igneous rocks.

855 [#21 – *Chemical precipitates*]: A wide variety of near-surface processes accompanied
856 the establishment of subaerial continental and shallow marine environments, resulting in
857 the formation of more than 1100 mineral species. Continental margins and lake
858 environments saw significant chemical precipitation of carbonates (Falkowski et al. 2000;
859 Boggs 2006), phosphorites (Baturin and Bezrukov 1979; Button 1982; Delaney 1998),
860 and iron formations (Klein 2005; Bekker et al. 2010), with at least 79 associated mineral
861 species. Extensive abiotic carbonate formations were especially consequential for
862 environmental changes in the Hadean Eon, as they rapidly became the dominant crustal
863 carbon reservoir, mirrored by a dramatic reduction of atmospheric CO₂ (Falkowski et al.
864 2000).

865 [#22 – *Low-T aqueous alteration*]: Hydration and low-temperature aqueous alteration
866 of a wide range of lithologies in shallow subsurface environments must have occurred as
867 soon as surface rocks were exposed to water. We estimate that Hadean aqueous alteration
868 led to 247 mineral species, including numerous hydrous silicates, hydrated phosphates in

869 altered granitic rocks, and more than 50 altered Mn minerals (Savage et al. 1987; Post
870 1999; Nishimoto and Yoshida 2010).

871 [#23 – *Subaerial aqueous alteration*]: We record an additional 398 minerals formed
872 by subaerial and near-surface aqueous alteration prior to significant oxidation (i.e., > 3
873 Ga). Many of these phases, notably including hydrous silicates, carbonates, phosphates,
874 and borates, likely form today in relatively reducing environments (Chang et al. 1996).
875 This suite of several hundred mineral species contrasts with the almost 2000
876 oxidized/weathered species that appeared following the GOE (< 3 Ga) [#47].

877 [#24 – *Terrestrial authigenic minerals*]: We identify 74 minerals that likely formed in
878 continental sediments as authigenic species, in contrast to marine authigenic phases
879 [#17]. Most of these minerals are relatively common silicates, carbonates, or phosphates
880 that are known to form in a variety of environments (Chang et al 1996; Deer et al. 2006).

881 [#25 – *Evaporites*]: The emergence of dry continental crust, with the likely occurrence
882 of extensive inland seas, saw increased opportunities for deposition of diverse evaporite
883 minerals (Button 1982; Buick and Dunlop 1990). We catalog 210 plausible phases;
884 however, the relative chronology of their first appearances, which must have been
885 strongly tied to composition, is not known. Halides, notably halite (NaCl) and sylvite
886 (KCl), must have formed on Earth's first shorelines in the early Hadean Eon. Sulfates
887 may have followed soon thereafter, especially if abiotic sulfur photo-oxidation played a
888 significant role in near-surface processes (see mode [#28] below). However, it may have
889 taken much longer for significant deposition of borates or nitrates to occur (e.g., Grew et
890 al. 2011, 2015).

891 [#26 – *Detrital minerals*]: Numerous mechanically robust minerals, including dozens
892 of metal alloys, carbides, and chalcogenides not yet discovered *in situ*, are preserved in
893 sediments as detrital minerals (Baker 1962). We list 250 detrital mineral species that we
894 suggest were present by the Hadean or Archean Eons. We have attempted to assign most
895 of these phases to other paragenetic modes, as well, based on their chemistries and
896 assumed lithological associations. Note, however, that in a few instances the original
897 contexts of detrital minerals are unknown [e.g., enigmatic tantalcarbide (TaC) and
898 niobocarbide (NbC)]; therefore, in these few examples the true paragenetic mode is
899 unresolved.

900 [#27 – *Radioactive processes*]: A number of minor but intriguing paragenetic
901 processes led to the formation of idiosyncratic minerals in near-surface environments. For
902 example, primary uranium minerals of the Hadean Eon would have invariably formed as
903 U^{4+} phases, most commonly uraninite (UO_2) and coffinite ($USiO_4$). However,
904 radioactive decay of U^{4+} to Pb^{2+} led to the intriguing phenomenon of “auto-oxidation,”
905 by which uranium is oxidized to U^{6+} (Frondel 1958; Finch and Murakami 1999; Hazen et
906 al. 2009, and references therein). Auto-oxidation resulted in localized formation of a few
907 uranyl-oxide-hydroxide phases, notably ianthinite [$U^{4+}(U^{6+}O_2)O_4(OH)_6(H_2O)_9$],
908 schoepite [$(UO_2)_8O_2(OH)_{12}(H_2O)_{12}$], and becquerelite [$Ca[(UO_2)_3O_2(OH)_3]_2(H_2O)_8$],
909 as well as Pb-bearing phases such as fourmarierite [$Pb[(UO_2)_4O_3(OH)_4](H_2O)_4$],
910 kasolite $[Pb[(UO_2)(SiO_4)](H_2O)]$, and vandendriesscheite
911 [$Pb_{1.5}[(UO_2)_{10}O_6(OH)_{11}](H_2O)_{11}$].

912 [#28 – *Photo-alteration*]: Early Earth did not have a protective ozone layer; therefore,
913 the near-surface environment was highly susceptible to UV photo-oxidation – a
914 potentially widespread but as yet incompletely studied phenomenon. A limited number of
915 minerals are known from laboratory studies to form by photo-oxidation processes (e.g.,
916 Kim et al. 2013); we list 10 of these species. In some instances, such as pararealgar
917 (AsS), digenite (Cu_{1.8}S), and ramsdellite (MnO₂), new minerals are known to form from
918 prior minerals that are exposed to visible light or ultraviolet radiation. Less well studied
919 are processes by which UV oxidation produces reactive oxidized chemicals, notably the
920 conversion of aqueous Fe²⁺ to Fe³⁺ with associated reduction of water and release of H₂.
921 Recent experiments by Yee and colleagues (Nathan Yee, personal communication, 7
922 February 2021) reveal that Fe³⁺ is a strong oxidant that can lead, for example, to abiotic
923 production of elemental selenium and sulfate minerals from primary selenides and
924 sulfides in anoxic environments. One can infer that many analogous reactions might have
925 occurred during the Hadean and early Archean Eons, for example producing a suite of
926 arsenate and antimonate minerals from precursor arsenides and antimonides. We are not
927 yet able to definitively catalog such prebiotic oxidized phases; however, the possibility
928 remains that significant mineral diversity arose indirectly through photo-oxidation prior
929 to the Great Oxidation Event (*Stage 7*).

930 [#29 – *Lightning minerals*]: A small suite of 9 highly-reduced minerals, including
931 silicon metal, graphite, iron, moissanite, and schreibersite, is associated with the
932 production of fulgurites by lightning strikes (Essene and Fisher 1986; Grapes 2006; Pasek
933 et al. 2012; Hess et al. 2021). Pasek and Block (2009) suggested that lightning-induced

934 reduction of phosphate minerals might have provided a source of biologically useful P
935 compounds prior to life's origins – an idea amplified by Hess et al. (2021).

936 [#30 – *Terrestrial impact minerals*]: Bolide impacts on exposed Hadean crust must
937 have produced a range of high-pressure shock-induced phases. We tabulate 16 known
938 impact species, including high-pressure forms of carbon (diamond), SiO₂ (coesite,
939 stishovite, and chaoite), TiO₂ (riesite and akaogiite), and other oxides and silicates
940 (Tomioka and Miyahara 2017; Tschauer 2019).

941 [#31 – *Thermal alteration*] Thermal metamorphism of diverse lithologies, including
942 sediments, igneous rocks, and metal-rich deposits, led to more than 1500 new phases
943 produced in subsurface continental environments. We tabulate 356 minerals that were
944 produced by thermal alteration reactions of prior phases with aqueous fluids, notably
945 those rich in carbonate and phosphate, as well as sulfate, borate, halogens, and other
946 solutes. Continents with deep roots and active hydrological cycles also hosted mineral
947 formation in more extreme subsurface environments, for example by high-temperature
948 alteration through metasomatism and/or contact metamorphism of carbonates (Falkowski
949 et al. 2000), phosphates (Button 1982), and iron formations (Klein 2005; Kappler et al.
950 2005).

951 [#32 – *Ba/Mn/Pb/Zn deposits*]: A remarkable variety of high-temperature minerals
952 containing Ba, Mn, Pb, and/or Zn, including contact and regional metamorphic deposits,
953 arose through processes in the continental crust (Post 1999; Leach et al. 2010). We
954 tabulate 412 species, including 185 phases unique to these environments, from classic
955 localities, including the Wessel manganese mine, South Africa (Caincross and Beukes
956 2013); Broken Hill, Australia (Spry et al. 2008); Fresno County, California (Alfors et al.

957 1965); and Franklin, Sussex County, New Jersey (Peters et al. 1983). These occurrences
958 underscore the importance of a few mineral-rich localities in establishing Earth's mineral
959 diversity.

960 [#33 – *Hydrothermal deposits*]: Subsurface hydrothermal deposition of metal-rich
961 veins and other bodies, primarily in environments associated with volcanism, produced ~
962 800 mineral species, most of which are unique to hydrothermal origins. Significant
963 uncertainties remain regarding the sequence and timing of the earliest appearances of
964 these varied, economically important sulfide, arsenide, selenide, antimonide, and related
965 sulfosalt minerals (Meyer 1988; Guilbert and Park 2007; Bradley 2011). We suggest that
966 early Hadean formations contained a relatively small subset of these phases, primarily
967 sulfides and some arsenides of the commoner transition elements; accordingly, we list
968 129 mineral species associated with mode [#12]. Note that prior to enhanced
969 mineralization associated with plate tectonics (Hazen et al. 2014; Groves et al. 2015),
970 most volcanism was likely associated with hot spots and vertical tectonics – processes
971 that may have been accompanied by far less crustal fluid-rock interactions than today's
972 subduction-related volcanism. We suggest that relatively few large-scale, metal-rich
973 hydrothermal systems would have occurred in those settings, analogous to what is
974 observed today at mineral-poor hot spots such as Hawaii, Yellowstone, and Iceland
975 (Sherman et al. 1968; Plazo-Toledo 2019). We conclude that the advent of subduction-
976 related volcanism, the appearance of volcano-hosted massive sulfide deposits, and the
977 associated concentrations of relatively rare elements were essential for the dramatic
978 expansion of hydrothermal mineral diversity.

979

980 Stage 4b. Highly evolved igneous rocks Significant mineral diversity is associated
981 with the concentration of rare, incompatible elements in late-stage magmas. “Complex”
982 granitic pegmatites, agpaitic and miaskitic pegmatites, carbonatites and related carbon-
983 rich magmas, and layered igneous intrusions with concentrations of PGE elements
984 account for 1476 mineral species, 662 of them unique to those compositionally
985 idiosyncratic environments. All of these lithologies were present by the end of the
986 Archean Eon; however, the timing of the most ancient of these formations is uncertain, as
987 their relative rarity, coupled with erosional loss, results in an imperfect record.

988 [#34 – *Complex granite pegmatites*]: We tabulate 564 mineral species that are found in
989 granite pegmatites, with 238 rare species known only from that environment. The earliest
990 documented occurrences of pegmatite minerals with essential Li and Be are from
991 Mesoarchean formations (~3.1 to 3.0 Ga), including the Barberton greenstone belt, South
992 Africa, and the Zishineni pegmatite, Swaziland (Tkachev 2011; Grew et al. 2017, 2019),
993 while the oldest known complex pegmatite with Cs mineralization is the 2.64 Ga Tanco
994 Mine in Manitoba, Canada (Černý 2005; London 2008). These earliest known examples
995 of complex granitic pegmatites may reflect the extreme concentration of rare elements
996 that was facilitated by subduction and consequent fluid-rock interactions in large volumes
997 of the crust and upper mantle, and thus only possible < 3 Ga.

998 [#35 – *Ultra-alkali rocks*]: Pegmatites from ultra-alkaline agpaitic and miaskitic rocks
999 display even greater mineral diversity than granite pegmatites, with 726 recorded species
1000 (Marks and Markl 2017; Mikhailova et al. 2019), including 377 minerals that are unique
1001 to agpaitic formations. Much of this mineralogical diversity results from the unusual

1002 concentration of Be, Ti, Y, Zr, Nb, and rare earth elements in these alkali-rich, silica-poor
1003 rocks.

1004 [#36 - *Carbonatites*]: Carbonatites, kimberlites, and related carbonate-bearing igneous
1005 rocks (Mitchell 1986; Jones et al. 2013) hold 291 distinctive minerals, including dozens
1006 of rare carbonate and phosphate species. These intriguing lithologies have been present
1007 since at least the Mesoarchean Era. Among the oldest known occurrences are the 3.01 Ga
1008 Tupertalik carbonatite from Greenland (Downes et al. 2012), and the 2.6 Ga Siilinjarvi
1009 carbonatite from Finland (Patchett et al. 1982; Woolley and Kjarsgaard 2008), whereas
1010 the Ol Doinyo Lengai volcano in Tanzania continues to erupt low-viscosity carbonate
1011 lavas.

1012 [#37 – *Layered igneous intrusions*]: In spite of their affinity to other mafic/ultramafic
1013 igneous rocks, we consider layered igneous intrusions to be a separate paragenetic
1014 environment because of their unusual homogeneous aerial extent, their predominantly
1015 Precambrian ages, and the common occurrence of metal-enriched layers with more than
1016 100 PGE and Cr-Ti-Fe oxide mineral species, including a number of phases reported
1017 from no other source (Naldrett et al. 1987; Maier and Groves 2011; Zientek 2012;
1018 O’Driscoll and VanTongeren 2017). The oldest known PGE deposit is the 3.2 Ga Baula
1019 deposit in India (Augé et al. 1993), with several Neoproterozoic and Paleoproterozoic
1020 examples recorded from localities in Africa and North America (Maier and Groves
1021 2011).

1022

1023 Stage 5. Initiation of plate tectonics Crustal recycling via plate tectonics was a
1024 significant driver of mineral diversification, largely as a consequence of mineralization

1025 associated with orogenesis, as well as the first subaerial exposure of otherwise hidden
1026 high-*P-T* lithologies. We adopt the prevailing view that modern-style, subduction-driven
1027 plate tectonics was well established prior to 3 Ga, as manifest in the Wilson cycle and
1028 episodes of supercontinent assembly (Huston et al. 2010; Nance et al. 2014; Hazen et al.
1029 2014), with significant earlier crustal recycling perhaps before 4 Ga (e.g., Condie and
1030 Pease 2008; Korenaga 2021).

1031 [#38 – *Ophiolites*]: The stranding of ophiolites, which are highly altered sequences of
1032 mafic and ultramafic rocks from the deep oceanic lithosphere, provides an important
1033 glimpse of the mineralogy and petrology of the crust-mantle boundary (Moores 2002;
1034 Dilek 2003; Kusky 2004). Ophiolites, which hold at least 108 mineral species, are in
1035 many respects similar to ocean floor rocks altered by serpentinization. However, their
1036 unique subaerial settings and exposures of mantle lithologies warrants a separate
1037 paragenetic category. Furthermore, the mineralogically unique Luobusha ophiolite from
1038 the Shannan Prefecture of Tibet is of special interest for a remarkable suite of dozens of
1039 UHP (e.g., diamond and moissanite) and highly-reduced phases, including native
1040 elements (Al, Cr, Cu, Fe, Ti, W), carbides, nitrides, and phosphides (Bai et al. 2011). In
1041 addition, the Luobusha occurrence features many PGE metal alloys (including
1042 approximately 30 as yet undescribed metal phases), in association with chromitite zones
1043 that are reminiscent of assemblages in layered intrusions [#37]. We include these diverse,
1044 rare minerals under ophiolites, though details of their paragenesis remain obscure.

1045 Debates persist regarding the oldest ophiolite. Furnes et al. (2007) suggested that an
1046 altered dike complex in Greenland's 3.8 Ga Isua supracrustal belt represents a "vestige"
1047 of oceanic crust, though this interpretation was questioned by Nutman and Friend (2007).

1048 The next oldest claim, the 2.5 Ga Dongwanzi ophiolite complex from China (Kusky et al.
1049 2001) has also been debated (Zhai et al. 2002; Kusky and Zhai 2012); however,
1050 descriptions of several altered Neoproterozoic examples support an origin by at least 2.5 Ga
1051 (Kusky 2004), providing further evidence that plate tectonics was well established in the
1052 late Archean Eon.

1053 [#39 – *High-P metamorphism*]: Plate tectonic processes have also led to the exposure
1054 of metamorphic rocks from environments with unusually low geothermal gradients,
1055 estimated to be < 10 °C/km – conditions only possible during relatively rapid subduction
1056 of crustal rocks to great depths, with subsequent buoyant uplift (Chopin 1984; Hacker
1057 2006; Palin and White 2016; Zheng and Chen 2017). These rocks include blueschist
1058 facies with glaucophane, jadeite, and/or lawsonite (formed at depths to 30 km); eclogite
1059 with pyrope and omphacite (> 45 km); and so-called “ultra-high pressure” (UHP)
1060 formations, featuring the dense coesite form of SiO₂ (> 80 km). The oldest known
1061 examples of these high-pressure lithologies are from the Neoproterozoic Era (~2.8 Ga),
1062 which coincides with models of plate tectonics commencing at ~3 Ga (Jahn et al. 2001;
1063 Brown 2007). We list 70 associated minerals, of which a dozen species, including
1064 trinepheline (NaAlSiO₄), kokchetavite (KAlSi₃O₈), and barioperovskite (BaTiO₃), are
1065 unique to these high-pressure metamorphic rocks.

1066 [#40 – *Regional metamorphism*]: Regional metamorphism associated with burial,
1067 alteration, and uplift of thick accumulations of sediments, volcanic rocks, and intrusive
1068 igneous rocks led to 319 mineral species. Most regional metamorphic rocks formed at
1069 depth under an average geothermal gradient of > 15 °C/km to ~30 °C/km (Vernon 2008;
1070 Philpotts & Ague 2009). These rocks are usually subdivided into facies based on the

1071 appearance of new minerals with increasing *P* and *T*: greenschist (typically with chlorite,
1072 serpentine, and epidote), amphibolite (amphibole and plagioclase), and granulite
1073 (pyroxene and plagioclase). We lump all of these regional metamorphic facies in this
1074 study, while acknowledging that further subdivision of metamorphic lithologies may be
1075 warranted in future studies.

1076 [#41 – *Mantle metasomatism*]: Mantle metasomatism (Luth 2003; O'Reilly and
1077 Griffin 2012) is a high-pressure hydrothermal metamorphic process that alters the
1078 chemistry of existing ultramafic minerals and produces new phases through interactions
1079 with deep C-O-H fluids (Manning and Frezzotti 2020). We identify 16 oxide and silicate
1080 mineral species formed through mantle metasomatism, all but 1 of which (nixonite,
1081 Na₂Ti₆O₁₃; Anzolini et al. 2019) are well known from other environments.

1082 [#42 – *Seafloor nodules*]: Seafloor nodules are enigmatic Mn- and Fe-rich concretions
1083 with significant Ni, Cu, and Co content that form extensive (and potentially economic)
1084 deposits on some regions of the ocean floor. While these nodules may be authigenic and
1085 thus a subset of mode [#17], their mineralogy and morphology appear to be distinct. If, as
1086 some contend, they form through microbial mineralization (Lysyuk 2008; Blöthe et al.
1087 2015) or through precipitation in an oxic environment (Fike et al. 2006; Wegorzewski
1088 and Kuhn 2014), then this paragenetic category should be moved to *Stage 6* or *Stage 7*.
1089 If, on the other hand, they form by the release and reprecipitation of metals from
1090 ultramafic rocks and/or from hydrothermal vents (Hlawatsch et al. 2002), then metal-rich
1091 nodules may have appeared as early as *Stage 3* or *Stage 4*. We provisionally assign
1092 seafloor nodules to *Stage 5*, based on the assumption that Mn release increased at

1093 spreading centers following the crustal recycling of plate tectonics. We list 15 minerals
1094 from Mn nodules, 11 of which are Mn or Fe oxides/hydroxides.

1095 [#43 – *Shear-induced minerals*]: Minerals produced by significant shear strain
1096 represent a distinct paragenetic mode, most commonly associated with polished fault
1097 surfaces known as slickensides (Passchier and Trouw 2005; Trouw et al. 2009). The
1098 closely related term “mylonite” relates to an altered zone of minerals recrystallized
1099 through shearing. We list 9 minerals produced in shear zones, 8 of which are common
1100 oxides and silicates, that are reported to form anew in silicate rocks through this process.
1101 It is difficult to assess when shear-generated minerals first occurred. We associate them
1102 primarily with plate tectonic processes, but some examples must have occurred as early
1103 as the Hadean Eon. On the other hand, of special interest is the rare chlorite group
1104 mineral, donbassite $[Al_2(Si_3Al)O_{10}(OH)_2 \cdot Al_{2.33}(OH)_6]$, which has been reported from
1105 slickensides of coal (Anthony et al. 1990-2003), and therefore must have formed at < 350
1106 Ma.

1107

1108 Stage 6. Anoxic biosphere [#44]: The rise of microbial life ~4.0 billion years ago appears
1109 to have had little initial impact on mineral diversity. However, some microbes learned to
1110 exploit minerals, using carbonates and phosphates as sturdy stromatolitic habitats
1111 (Chauhan 1979; Burnett and Riggs 1990; Cook and Shergold 1990; Grotzinger and Knoll
1112 1999; Van Kranendonk et al. 2003), as well as employing iron (and possibly other
1113 transition metal) oxide and sulfide phases as reliable sources of redox energy (Lowell et
1114 al. 2009; Ishibashi et al. 2015). We propose a conservative list of 11 microbially-
1115 mediated minerals, all of them common phases found in five or more paragenetic

1116 environments, that are thought to have formed in anoxic environments prior to the rise of
1117 atmosphere that characterized *Stage 7*. Numerous instances of Archean minerals
1118 precipitated through microbial action have been documented (Grotzinger and Knoll 1999;
1119 Konhauser et al. 2002; Frankel and Bazylnski 2003; Schulz and Schulz 2005; Southam
1120 and Saunders 2005; Lepot et al. 2008). Unambiguous occurrences of microbial carbonate
1121 stromatolites occur as early as 3.5 Ga in rocks of the Pilbara craton in Western Australia
1122 (Van Kranendonk et al. 2003; Allwood et al. 2006), pointing to calcite, dolomite, and
1123 siderite as likely early biominerals. Similarly, biogenic phosphatic stromatolites
1124 (Banerjee 1971; Schulz and Schulz 2005) and iron formations (Anbar and Holland 1992;
1125 Akai et al. 1999) have been described from multiple localities as early as the Neoproterozoic
1126 Era.

1127

1128 *Stage 7. Great Oxidation Event* The single most significant factor in Earth's mineral
1129 diversification was the Neoproterozoic/Paleoproterozoic rise of atmospheric oxygen, which
1130 we estimate led to the introduction of more than 2300 new mineral species. However, at
1131 least two significant uncertainties relate to the timing and nature of the formation of
1132 Earth's diverse oxidized mineral species.

1133 A persistent question relates to the timing of atmospheric oxygenation (Canfield 2014;
1134 Lyons et al. 2014). A number of early Earth scenarios point to the Great Oxidation Event
1135 as a prolonged period of atmospheric change, often modeled as occurring after 2.4 Ga,
1136 when global-scale oxygenic photosynthesis became well established. Important evidence
1137 for this change in atmospheric composition is found in the sulfur isotope record, notably
1138 in the disappearance of mass-independent S isotope fractionation in near-surface sulfur-

1139 bearing minerals (Farquhar et al. 2000, 2001, 2007). This rather abrupt change in the
1140 character of S isotope ratios is thought to have occurred owing to formation of a UV-
1141 blocking ozone layer. However, other researchers point to intervals or oases of elevated
1142 atmospheric oxygen as early as 3.1 Ga based on pulses of redox-sensitive trace elements
1143 in Archean sediments (e.g., Anbar et al. 2007), as well as the postulated early appearance
1144 of microbial oxygen-utilizing enzymes (Jabłońska and Tawfik 2021). Those results
1145 suggest that a subset of oxidized mineral species might have formed prior to 2.4 Ga,
1146 during the Neoproterozoic Era.

1147 A second uncertainty relates to the extent of Archean *abiotic* processes that might
1148 have produced relatively oxidized mineral species. In particular, as noted above (see
1149 [#28]), UV-photooxidation of Fe^{2+} to Fe^{3+} , followed by production of sulfates and other
1150 relatively oxidized minerals, may have been a ubiquitous process in near-surface waters
1151 prior to the establishment of a UV-blocking ozone layer. If this UV-mediated process was
1152 commonplace prior to the rise of atmospheric oxygen, then some of the relatively
1153 oxidized phases we ascribed to post-GOE biological O_2 production may have emerged
1154 much earlier through abiotic chemistry. With those caveats in mind, we consider three
1155 important mineral-forming environments that were strongly influenced by atmospheric
1156 oxygenation.

1157 [#45 – *Volcanic fumarole minerals, oxidized*]: Volcanic fumaroles produce a
1158 remarkable variety of more than 420 relatively oxidized mineral species, 168 of which
1159 are unique to volcanic vents. We suggest that these minerals could only have been
1160 precipitated after the GOE (e.g., Vergasova and Filatov 2016). Accordingly, we tabulate
1161 253 fumarolic sulfates, arsenates, selenates, and antimonates, as well as 171 other vent

1162 minerals, including carbonates, borates, nitrates, phosphates, and other phases
1163 incorporating a range of transition metals (V, Cr, Zn, Mo, W), halogens, and ammonia.
1164 We include intriguing pneumatolytic minerals [e.g., itelmenite, $\text{Na}_2\text{CuMg}_2(\text{SO}_4)_4$;
1165 Nazarchuk et al. 2018] that are thought to form by reactions of prior minerals with
1166 fumarolic gases (Krivovichev et al. 2013).

1167 [#46 – *Oxidized hydrothermal minerals*]: The formation of more than 2000 secondary
1168 minerals by near-surface “weathering,” primarily oxidation and hydration, is by far the
1169 greatest single contributor to Earth’s mineral diversity. The majority of these minerals
1170 form in direct contact with the oxygenated atmosphere (see [#47]). However, we
1171 distinguish 52 oxidized secondary minerals, primarily sulfates and arsenates, that are
1172 described as forming in hydrothermal environments. Thus, for example, mansfieldite
1173 $[\text{AlAsO}_4 \cdot 2\text{H}_2\text{O}]$ is reported by Anthony et al. (2003) to be “a hydrothermal product in
1174 altered and mineralized andesitic pyroclastic rocks” (and thus included in [#46]), in
1175 contrast to its Fe-bearing isomorph scorodite $[\text{Fe}^{3+}\text{AsO}_4 \cdot 2\text{H}_2\text{O}]$, which is described as “a
1176 secondary mineral formed by oxidation of As-bearing sulfides” and therefore assigned to
1177 [#47]. Similarly, cesanite $[\text{Ca}_2\text{Na}_3[(\text{OH})(\text{SO}_4)_3]]$ (Cavarretta et al. 1981) and grandaite
1178 $[\text{Sr}_2\text{Al}(\text{AsO}_4)_2(\text{OH})]$ (Cámara et al. 2014) are described as hydrothermal minerals,
1179 whereas compositionally similar antofagastaite $[\text{Na}_2\text{Ca}(\text{SO}_4)_2 \cdot 1.5\text{H}_2\text{O}]$ (Pekov et al.
1180 2019) and arsenogoyazite $[\text{SrAl}_3(\text{AsO}_4)(\text{AsO}_3\text{OH})(\text{OH})_6]$ (Walenta and Dunn 1984) are
1181 presented as secondary oxidized phases. We have adopted the reported paragenetic
1182 modes of these oxidized minerals – hydrothermal versus secondary – while recognizing

1183 that a continuum exists for secondary oxidized minerals formed in near-surface
1184 environments.

1185 [#47 – Oxidative weathering]: We catalog 1998 secondary minerals formed in low-
1186 temperature weathering environments in contact with a post-GOE oxygenated
1187 atmosphere. Given this large number of secondary, oxidized minerals (35 % of all IMA-
1188 approved species), we subdivide these phases into 9 overlapping compositional groups.
1189 Near-surface hydration of prior minerals is the largest subset, with 1649 species (82.5 %
1190 of [#47]). Other subsets include sulfates and sulfites (409 species); carbonates,
1191 phosphates, borates, and nitrates (577); arsenates, antimonates, selenates, and
1192 bismuthinates (505); vanadates, chromates, and manganates (372); uranyl (U^{6+}) minerals
1193 (236); and halogen-bearing minerals (236). A significant subset (316 species) of these
1194 weathering products are dehydrated, which may point to multiple stages of subaerial
1195 weathering that included both hydration and dehydration reactions. Finally, we include
1196 28 minerals known to form through the terrestrial weathering of meteorites [#47i],
1197 including 10 Fe, Ni, and/or Cr phases only known from the alteration of iron meteorites
1198 (Rubin and Ma 2021).

1199 An intriguing finding is that 1119 of these minerals – 20 % of Earth’s total mineral
1200 diversity – are known to form only through paragenetic mode [#47]. These species
1201 formed exclusively by oxidative weathering are not equally divided among the 9
1202 compositional groups (Table 1). Approximately 45 % of sulfates and 51 % of halogen-
1203 bearing phases in [#47] are only known as weathering phases, whereas 73 % of uranyl
1204 minerals are uniquely found in those near-surface oxidized environments.

1205

1206 Stage 8. Intermediate Ocean A billion years of the Proterozoic Eon (~1.8 to 0.8 Ga) was
1207 evidently a period of gradual oxygenation of the “intermediate ocean” (Anbar and Knoll
1208 2002), coupled with reduced mineralization (Hazen et al. 2008; Bradley 2011; Hazen et
1209 al. 2014; Liu et al. 2019). Sometimes called the “boring billion” (Brasier 1998, 2012;
1210 Buick et al. 1995), this extended Proterozoic interval appears to have seen no new
1211 paragenetic processes.

1212

1213 Stage 9. Snowball Earth The end of the Neoproterozoic Era (~0.8 to 0.6 Ga) featured at
1214 least three major episodes of global glaciation, when ice was the dominant mineral over
1215 most of Earth’s surface from poles to Equator (Kirschvink 1992; Hoffman et al. 1998).
1216 Each of these “snowball Earth” events saw the cessation of significant continental
1217 weathering, while atmospheric carbon dioxide increased through the contributions of
1218 continuous volcanic emissions – changes that in turn led to an exaggerated greenhouse
1219 effect, global warming, and episodes of relatively rapid loss of ice cover. These
1220 intervening “hothouse Earth” periods must have seen enhanced surface weathering,
1221 notably accompanied by carbonate formation. However, no new paragenetic processes
1222 are associated with *Stage 9* of mineral evolution.

1223

1224 Stage 10a. Neoproterozoic oxygenation and the Phanerozoic biosphere The Phanerozoic
1225 Eon (< 541 Ma) has been characterized by significant mineralogical novelty, with almost
1226 600 new minerals, notably those arising from biological (including anthropogenic)
1227 processes. Distinctions have been proposed by Perry et al. (2007) between “biominerals”
1228 (produced by living cells) and “organominerals” (derived from organic molecules, often

1229 taphonomic, but not directly produced by cellular activity). We further recognize
1230 thousands of biologically-mediated mineral species that form indirectly as a consequence
1231 of environmental changes caused by cellular activity – most significantly oxygenic
1232 photosynthesis.

1233 [#48 – *Soil minerals*]: Research in paleopedology – the study of ancient soils or
1234 “paleosols” – reveals that Earth’s terrestrial surface has been coated by fine-grained
1235 detrital material for much of its history (Johnson and Watson-Stegner 1987; Holland and
1236 Rye 1997; Rye and Holland 1998; Retallack 2001). However, prior to the emergence of
1237 land plants at ~0.4 Ga soils tended to be thin and mineralogically tied to their host
1238 lithologies and subaerial weathering. Soils became much deeper and more complex
1239 mineral-producing zones in concert with the development of root systems, most notably
1240 following the evolution of symbiotic mycorrhizal fungi (Remy et al. 1994; Paris et al.
1241 1995, 1996; Ueshima and Tazaki 1998). The terrestrial formation of clay minerals in
1242 soils, in particular, is estimated to have increased by an order of magnitude with the
1243 advent of root systems (Schwartzman and Volk 1989; Barker et al. 1998). We list 71 soil
1244 minerals that we attribute to Phanerozoic processes, including more than a dozen Al-rich
1245 hydrous minerals from leaching zones in laterites and bauxites (e.g., Helgren and Butzer
1246 1977; Hill et al. 2000).

1247 [#49 – *Biominerals*]: Phanerozoic biomineralization encompasses a fascinating
1248 collection of 77 minerals formed by a variety of metabolic processes. Much attention has
1249 focused on the biological nano-sculpting of mineral-organic composite materials that play
1250 structural roles in organisms. Examples include hydroxylapatite and fluorapatite in
1251 directed biomineralization of vertebrates (teeth and bones), inarticulate brachiopod shells,

1252 and stinging nettles; the calcite or aragonite forms of CaCO_3 , for example in corals,
1253 mollusks, and foraminifera; and of silica employed by such diverse organisms as diatoms,
1254 sponges, and spinifex grass (Lowenstam and Weiner 1989; Weiner and Wagner 1998;
1255 Dove et al. 2003; Dove 2010; Aparicio and Ginebra 2016; Ensikat et al. 2016; Kattimani
1256 et al. 2016; Endo et al. 2018). Lichtenegger et al. (2002) also reported an unusual
1257 occurrence of atacamite [$\text{Cu}_2(\text{OH})_3\text{Cl}$] in jaws of the bloodworm, *Glycera dibranchiate*.

1258 Microbially-induced oxidation-reduction reactions have resulted in a variety of
1259 mineralization pathways, including reduction of aqueous U^{6+} to uraninite (UO_2 ; Suzuki
1260 and Banfield 1999; Fayek et al. 2005; Hazen et al. 2009; Wufuer et al. 2017); formation
1261 of autunite group uranium phosphates (Liang et al. 2015; Beazley et al. 2017); oxidation
1262 or reduction of iron oxide, sulfide, or sulfates (Pósfai et al. 1998; Akai et al. 1999; Coker
1263 et al. 2008; Boyd and Druschel 2013; Berg et al. 2014, 2020), notably to form internal
1264 “magnetosomes” of magnetite or greigite for microbial navigation (Chang and
1265 Kirschvink 1989; Lins et al. 2007; Pósfai et al. 2013; Uebe and Schüler 2016); and
1266 manganese redox reactions to form a number of species [e.g., vernadite, todorokite,
1267 birnessite, rhodochrosite; Carmichael and Bräuer 2015; Kelm et al. 2015; Li et al. 2016;
1268 Zerfaß et al. 2019; Galezowski et al. 2020; Lu et al. 2021). Some researchers have
1269 suggested that seafloor manganese nodules form, at least in part, through such
1270 biochemical processes (Lysyuk 2008; Blöthe et al. 2015). Microbes have also been
1271 invoked in the precipitation of gold (Au; Reith et al. 2006, 2009; Johnston et al. 2013;
1272 Sanyal and Shuster 2021), copper carbonate (Li and Gadd 2017), anatase (TiO_2 ; Ping et

1273 al. 2016), vanadium minerals (Carpentier et al. 2003), and polymorphs of sulfur (Douglas
1274 and Yang 2002; Gleeson et al. 2011; Cron et al. 2019).

1275 Biochemical processes also lead to a variety of incidental minerals (Yoder 2002;
1276 Hazen et al. 2008, their Table 3), as manifest in dozens of human-precipitated minerals,
1277 for example in kidney stones (Rogers 1997; Giannossi et al. 2009) and gallstones (Endo
1278 1962; Dumitraşcu et al. 1984). Finally, the only example of a mineral known to form
1279 exclusively by biomineralization is hazenite $[\text{KNaMg}_2(\text{PO}_4)_2 \cdot 14\text{H}_2\text{O}]$; Yang et al. 2011],
1280 which is excreted by microbes living in the alkali- and P-saturated hypersaline waters of
1281 Mono Lake, California.

1282 [#50 – *Coal minerals*]: An eclectic assortment of 273 different mineral species has
1283 been identified from coal and/or oil shale minerals, all of which must have been formed
1284 in the past ~300 million years (Saxby 2000; Schweinfurth 2016). As might be expected,
1285 several of these phases are crystallized hydrocarbons, such as idrialite ($\text{C}_{22}\text{H}_{14}$) and
1286 evenkite ($\text{C}_{23}\text{H}_{48}$), or ammonia-bearing minerals, including letovicite $[(\text{NH}_4)_3\text{H}(\text{SO}_4)_2]$
1287 and godovikovite $[(\text{NH}_4)\text{Al}(\text{SO}_4)_2]$. Of note is abelsonite ($\text{NiC}_{31}\text{H}_{32}\text{N}_4$; Milton et al.
1288 1978), the only known geoporphyry mineral, from the Green River oil shale of Utah.
1289 Coal and oil shale also contain a wide range of fine-grained clay minerals,
1290 oxide/hydroxides, and hydrous sulfates, as well as minerals incorporating relatively rare
1291 metals that are known to concentrate in hydrocarbon-rich deposits, for example
1292 strangersite (SnGeS_3), patronite (VS_4), Laphamite (As_2Se_3), cadmoindite (CdIn_2S_4),
1293 moschelite (HgI), tugarinovite (MoO_2), bismuthinite (Bi_2S_3), and stibnite (Sb_2S_3). Note

1294 that we also list 234 minerals produced in coal mine fires as a separate anthropogenic
1295 paragenetic process [#54]. However, we cannot rule out possible overlaps between those
1296 phases and the varied coal minerals listed here [#50].

1297 [#51 – *Pyrometamorphic minerals*]: Pyrometamorphic minerals of the Hatrurim
1298 Formation in the Middle East (Israel and Jordan) include a fascinating suite of 128
1299 species that formed when natural ignition of near-surface hydrocarbon deposits
1300 (presumably both natural gas and petroleum) subjected sediments to temperatures in
1301 excess of 1000 °C (Gross 1977; Grapes 2006; Sokol et al. 2019). Two-thirds of these
1302 minerals are Ca-bearing, some closely resembling phases in cement “clinkers,” including
1303 such unusual silicates as larnite (Ca₂SiO₄), hatrurite (Ca₃SiO₅), grossite (CaAl₄O₇), and
1304 rankinite (Ca₃Si₂O₇). The Hatrurim Formation also hosts unusual Ca sulfides such as
1305 oldhamite (CaS) and dzierzanowskite (CaCuS₂), and other phases such as vapnikite
1306 (Ca₃UO₆), chromatite (CaCrO₄), and lakargite [Ca(Zr,Sn)O₃]. The Hatrurim Formation
1307 is mineralogically unique, but pyrometamorphism has been a persistent phenomenon
1308 throughout Earth history, with high-*T*, low-*P* alteration occurring in lava xenoliths [#9],
1309 during lightning strikes [#29], and as a consequence of anthropogenic coal mine fires
1310 [#54] and smelting [#56].

1311 [#52 – *Guano/urine minerals*]: A curious assortment of 72 mineral species are derived
1312 from the urine and guano of birds and bats – minerals preserved primarily in caves and on
1313 islands in arid environments. A few of these minerals form directly from excreta,
1314 including guanine [C₅H₃(NH₂)N₄O], urea [CO(NH₂)₂], and uricite (C₅H₄N₄O₃). Other
1315 minerals result from reactions between urine and prior minerals; spheniscidite

1316 $[(\text{NH}_4)\text{Fe}^{3+}_2(\text{PO}_4)_2(\text{OH})\cdot 2\text{H}_2\text{O}]$ (Wilson and Bain 1986), a fascinating example, is
1317 formed when the urine of penguins (order *Sphenisciformes*, hence the mineral name)
1318 reacts with layer silicates in soils beneath a rookery on Elephant Island in the British
1319 Antarctic Territory.

1320 [#53 – *Taphonomic minerals*]: We identify 117 other biologically-derived minerals
1321 with presumed taphonomic origins, mostly formed during the decay and/or fossilization
1322 of wood and other plant material (Behrensmeier et al. 2000, Mustoe 2018). Plant decay
1323 leads to several distinctive organic minerals (e.g., Garvie 2003), notably oxalates, such as
1324 weddellite ($\text{CaC}_2\text{O}_4\cdot 2\text{H}_2\text{O}$) and uroxite $[(\text{UO}_2)_2(\text{C}_2\text{O}_4)(\text{OH})_2(\text{H}_2\text{O})_2\cdot \text{H}_2\text{O}]$, and acetates,
1325 including paceite $[\text{CaCu}(\text{CH}_3\text{COO})_4\cdot 6\text{H}_2\text{O}]$ and hoganite $[\text{Cu}(\text{CH}_3\text{COO})_2\cdot \text{H}_2\text{O}]$. Decay
1326 may also release ammonia, which plays a role in producing 20 taphonomic minerals that
1327 form by reaction with NH_4 -bearing fluids, for example ammoniozippeite
1328 $[(\text{NH}_4)_2(\text{UO}_2)_2(\text{SO}_4)\text{O}_2\cdot \text{H}_2\text{O}]$ and ambrinoite $[(\text{K},\text{NH}_4)_2(\text{As},\text{Sb})_6(\text{Sb},\text{As})_2\text{S}_{13}\cdot \text{H}_2\text{O}]$. An
1329 intriguing geochemical consequence of wood fossilization is the concentration of
1330 vanadium-rich fluids and formation of at least 14 minerals, including vanoxite
1331 $(\text{V}^{4+}_4\text{V}^{5+}_2\text{O}_{13}\cdot 8\text{H}_2\text{O})$ and dreyerite $(\text{Bi}^{3+}\text{V}^{5+}\text{O}_4)$. Burial of organics also commonly
1332 results in subsurface reduction reactions, including U^{6+} to U^{4+} [e.g., coffinite,
1333 $(\text{U}^{4+}\text{SiO}_4\cdot n\text{H}_2\text{O})$] and V^{5+} to V^{4+} or V^{3+} [berdesinskiite, $(\text{V}^{3+}_2\text{TiO}_5)$].

1334

1335 Stage 10b. Anthropogenic minerals The most recent (and ongoing) stage of mineral
1336 evolution, spanning the past few thousand years but intensifying since the Industrial

1337 Revolution, encompasses a wide range of more than 600 human-mediated minerals
1338 (Catheart 2011; Corcoran et al. 2014; Hazen and Zalaziewski 2019; Zeng et al. 2020).
1339 Hazen et al. (2017) reviewed the mineralogy of the so-called “Anthropocene Epoch,”
1340 tabulating 208 mineral species approved by the IMA-CNMNC that occur principally or
1341 exclusively through human activities. The present more inclusive survey of the
1342 paragenetic modes of all minerals points to more than 600 mineral species that may form
1343 as byproducts of human industry, though most of those phases occur by natural
1344 processes, as well.

1345 [#54 – *Mine fire minerals*]: Of more than 500 anthropogenic minerals arising as a
1346 consequence of mining activities, we tabulate 234 minerals that form in coal mine fires,
1347 both by thermal metamorphism of prior phases and by condensation of new species
1348 (Lapham et al. 1980; Grapes 2006; Kruszewski 2013; Stracher et al. 2015). All but 6 of
1349 these minerals are also known to form by other processes, mostly by pyrometamorphism
1350 [#51] and at volcanic fumaroles ([#11] or [#45]). Those six species unique to coal fires
1351 include two intriguing molecular crystals: freitalite ($C_{14}H_{10}$) is composed of the
1352 polycyclic aromatic hydrocarbon, anthracene, which is a major component of coal tar;
1353 acetamide (CH_3CONH_2) is the simplest amide (NH_2) compound, which has important
1354 uses in the plastics industry.

1355 [#55 – *Mine-derived minerals*]: Mining activities lead to a wealth of new minerals,
1356 including those formed by weathering of mine dump phases, formation on mine tunnel
1357 walls, precipitation from acid mine drainage systems, and alteration associated with mine
1358 timbers and artifacts (Hazen et al. 2017). We recognize 264 of these mining-derived
1359 minerals, all but 5 of which also form in natural environments. In particular, 227 of these

1360 species (86 %) also arise through natural near-surface oxidative weathering processes
1361 [#47]. We acknowledge that it is often difficult to discriminate between phases that arose
1362 exclusively because of human mining activities and those that may have formed naturally
1363 through alteration of surface exposures.

1364 [#56 – *Slag minerals*]: The alteration of minerals through smelting, and in some
1365 instances the subsequent alteration of slag, results in 143 mineral species. This high-
1366 temperature processing represents a form of pyrometamorphism (Grapes 2006; Sueoka
1367 and Sakakibara 2013; Kierczak and Ettler 2021), and it produces a similar suite of phases
1368 to other pyrometamorphic mechanisms (e.g., [#9], [#11], [#29], and [#54]). We did not
1369 identify any mineral species that occurs exclusively in slag.

1370 [#57 – *Other human-mediated minerals*]: Finally, we record an eclectic list of 49
1371 mineral species produced via other human-mediated processes. These phases include
1372 corrosion products of bronze, lead, and other ancient archaeological artifacts, notably Pb-
1373 and Cu-bearing phases that have been found associated with the ancient slag deposits at
1374 Laurium, Greece [e.g., atacamite, $\text{Cu}_2\text{Cl}(\text{OH})_3$, and laurionite, $\text{PbCl}(\text{OH})$; Smith and
1375 Prior 1899]; precipitation of phases in geothermal piping and other mineral-rich
1376 subsurface water systems, such as nasinite $[\text{Na}_2\text{B}_5\text{O}_8(\text{OH})\cdot 2\text{H}_2\text{O}]$ and santite
1377 $[\text{KB}_5\text{O}_6(\text{OH})_4\cdot 2\text{H}_2\text{O}]$ from Tuscany (Merlino and Sartori 1970); alteration of archived
1378 drill cores or minerals stored in museum drawers, including calclacite
1379 $[\text{Ca}(\text{CH}_3\text{COO})\text{Cl}\cdot 5\text{H}_2\text{O}]$; Van Tassel 1945] and coalingite
1380 $[\text{Mg}_{10}\text{Fe}^{3+}_2(\text{CO}_3)(\text{OH})_{24}\cdot 2\text{H}_2\text{O}]$; Mumpton et al. 1965]; minerals suspected of forming
1381 by grinding [itoite, $\text{Pb}_3\text{GeO}_2(\text{SO}_4)_2(\text{OH})_2$; Anthony et al. 2003]; fertilizer byproducts

1382 such as metavariscite $[\text{Al}(\text{PO}_4)\cdot 2\text{H}_2\text{O}]$; Anthony et al. 2003]; and alteration of discarded
1383 lead batteries (e.g., cerussite, PbCO_3). However, none of these phases is unique to
1384 anthropogenic activities, in accord with rules of the IMA-CNMNC (e.g., Nickel and
1385 Grice 1998). Other minerals that might join this list in the future include alteration phases
1386 of discarded lithium batteries, semiconductors and phosphors employed in electronics,
1387 and other technological materials (e.g., Galezowski et al. 2020).

1388 In addition, purposeful human productions of countless thousands of synthetic phases
1389 not considered as minerals by the IMA-CNMNC have dramatically increased the
1390 diversity and distribution of mineral-like compounds at or near Earth's surface. Many of
1391 these compounds, including building materials, semiconductors, laser crystals, specialty
1392 alloys, synthetic gemstones, and possibly even plastic debris, are likely to persist for
1393 millions of years in the geologic record, thus providing a clear sedimentary horizon that
1394 marks the Anthropocene Epoch (Catheart 2011; Corcoran et al. 2014; Hazen et al. 2017;
1395 Hazen and Zalaziewski 2019).

1396

1397

IMPLICATIONS

1398 This study of the paragenetic modes of minerals points to several important trends in
1399 mineral evolution, while raising significant unanswered questions. Our preliminary
1400 database records 5659 minerals approved by the IMA-CNMNC assigned to 57
1401 paragenetic modes, resulting in 10,556 combinations of a mineral species and a
1402 paragenetic mode (Supplementary Table 1). This open-access database is an evolving
1403 resource; we welcome additions and corrections.

1404 Several conclusions can be drawn from these data:

- 1405 • *Water is the principal driver of mineral diversity:* Of the 5659 minerals examined,
1406 4583 (81.0 %) either incorporate essential OH⁻ and/or H₂O, accounting for 3150 of
1407 5659 mineral species (55.7 %), or they are anhydrous phases that were formed
1408 through the action of aqueous fluids, for example, by dehydration, evaporation, or
1409 precipitation from a hydrothermal solution (1433 species). No other physical or
1410 chemical factor comes close to this dominant role of water in creating mineral
1411 diversity. Near-surface hydration and weathering represent obvious major factors in
1412 this variety, resulting in more than 2000 species. We suggest that subduction and the
1413 deep-water cycle is comparable in its influence on Earth's mineralogy as a
1414 consequence of the selection and concentration of rare elements through water-rock
1415 interactions in large volumes of the upper mantle and crust. The sharp contrast
1416 between Earth's large complement of minerals and the relative mineralogical
1417 parsimony of the Moon and Mercury, as well as the modest diversity found on Mars,
1418 stems from differing influences of water.

- 1419 • *Biology plays an important role in Earth's mineral diversity (but not quite as much*
1420 *as previously suggested):* We find that almost half of Earth's minerals – 2707 of
1421 5659 species (47.8 %) – are known to form as a result of biological influences. More
1422 than 2000 of these minerals occur as a consequence of near-surface oxidative
1423 weathering/alteration of prior phases, which is the second most important factor in
1424 Earth's mineral diversity after water. Many minerals also form as coal-related and
1425 other taphonomic minerals (597 species), as well as anthropogenic minerals, for
1426 example as byproducts of mining (603 minerals). However, contrary to previous
1427 estimates, we find that only ~34% of mineral species form *exclusively* as a
1428 consequence of biological processes, in contrast to the estimate of two-thirds by
1429 Hazen et al. (2008). Nevertheless, the appearance of more than 1900 minerals
1430 exclusively through biology represents a significant, pervasive planetary biomarker
1431 (Chan et al 2019; Johnson et al. 2020).
- 1432 • *Rare elements are important in Earth's mineral diversity:* As noted above, 41 rare
1433 mineral-forming elements present in Earth's crust at less than 5 ppm are essential
1434 constituents in ~2400 mineral species. These scarce elements, including
1435 chalcogenides (As, Sb, Se, Te), transition metals (Cd, Mo, Sn), platinum group
1436 elements, and rare earth elements, represent fewer than 1 in 10,000 crustal atoms, yet
1437 they are essential in 42.4 % of minerals (<https://rruff.info/ima>, accessed 7 March
1438 2021) – far more species than might be expected based on crustal abundances. We
1439 suggest that interactions between host rocks with trace amounts of these elements
1440 and aqueous fluids, especially with varied anionic species that select and concentrate
1441 metal ions, are the principal factor in creating local chemical anomalies with extreme

1442 rare element concentrations. This observation is consistent with the occurrence of
1443 mineral-rich localities associated with complex granite pegmatites, agpaitic rocks,
1444 and many hydrothermal ore deposits. In the context of evolving complex systems,
1445 including natural ecosystems and human societies, it is significant that the presence
1446 of a few exotic individuals has the potential to greatly enhance system diversity.

1447 • *Most minerals are known to form by only one paragenetic process:* Most mineral
1448 species – 3349 of 5659, or 59.2 % – are known to form by only one of our proposed
1449 57 paragenetic modes. An additional 1372 species (24.2 %) have two known
1450 paragenetic modes, whereas 458 species (8.1 %) have three. By contrast, only 26
1451 minerals, all of them familiar and abundant rock-forming phases (Deer et al. 1982-
1452 2013), are known to form in 12 or more different ways. Pyrite boasts the most
1453 diverse range, with 21 paragenetic modes, including igneous, metamorphic,
1454 sedimentary, and alteration host lithologies; encompassing both abiotic and biotic
1455 processes; and spanning more than 4.5 billion years of Earth history, from pre-
1456 terrestrial asteroid alteration (> 4.56 Ga) to precipitation in anthropogenic mine
1457 environments (< 1 Ka). Other widely-forming species with 14 or more paragenetic
1458 modes include albite, corundum, hematite, and magnetite (with 18 modes); calcite,
1459 hornblende, and rutile (17); baryte (15); and forsterite, ilmenite, quartz, and
1460 sphalerite (14). Note that the previous finding that most minerals are rare, found at
1461 five or fewer localities (Hazen et al. 2015; Hystad et al. 2015; Hazen and Ausubel
1462 2016), mirrors the observation that most minerals have only one mode of formation.

1463 Our work also raises intriguing questions that will drive future investigations:

- 1464 • *Does Earth's mineralogy display a progressive rise in complexity?* Pioneering work
1465 on the quantification of mineral complexity by Sergey Krivovichev (2012, 2013,
1466 2014, 2015, 2016) facilitates testing of hypotheses related to increased mineral
1467 complexity through time. Preliminary work has been applied to suites of minerals
1468 based on composition (Grew et al. 2016, 2017; Morrison et al. 2020) or approximate
1469 stage in Earth history (Krivovichev et al. 2018). The present study offers the
1470 opportunity to probe the evolving complexity of Earth's minerals in greater depth, by
1471 considering the relative influences of temperature, pressure, and/or composition in
1472 various mineral-forming environments as a function of geological time. Quantitative
1473 investigations of whether, and if so how, mineral system complexify over time could
1474 provide a rigorous test of models of cosmic chemical evolution (e.g., Zaikowski and
1475 Friedrich 2007).
- 1476 • *What mineral-forming environments occur on the Moon, Mars, and other terrestrial*
1477 *worlds?* Enumerating paragenetic modes, and placing each mineral species into one
1478 or more of those categories, offers an opportunity to evaluate extraterrestrial
1479 mineralogy with a new perspective. If Mars had (or still has) a hydrological cycle,
1480 what mineralogical manifestations might we expect? For example, are there Martian
1481 hydrothermal sulfide deposits and, if so, were a variety of metals mobilized? On the
1482 other hand, if the Moon is truly dry, then what paragenetic processes are excluded?
1483 And do extraterrestrial bodies display paragenetic processes not seen on Earth, such
1484 as cryo-volcanism on Titan (Maynard-Casely et al. 2018; Hazen 2018).
- 1485 • *What role did minerals play in the origins of life?* A recurrent theme in recent studies
1486 of Earth's evolving crust, in particular the tectonic processes that shaped it, is

1487 speculation that many of Earth's mineral-forming processes may have occurred
1488 much earlier than previously modeled. The formation of oceans prior to 4.45 Ga, the
1489 extensive development of continental crust by 4.4 Ga, and perhaps even the initiation
1490 of some form of subduction-driven plate tectonics in the early Hadean Eon, push
1491 many important mineral-forming processes to Earth's first 250 million years. These
1492 scenarios, if true, have important implications for models of mineral evolution and
1493 the origins of life. Previous estimates of Hadean mineral diversity posited
1494 mineralogical parsimony, with only a few hundred species prior to 4 Ga (Hazen
1495 2013; Morrison et al. 2018). However, this new tabulation of mineral paragenetic
1496 modes, coupled with recent estimates of the rapid evolution of a dynamic early
1497 Hadean Earth, suggest that as many as 3534 mineral species – the collective
1498 inventories of modes [#1] through [#43] – may have formed within Earth's first 250
1499 million years. If so, then most of the geochemical and mineralogical environments
1500 invoked in models of life's origins would have been present by 4.3 Ga. If life is rare
1501 in the universe, requiring an idiosyncratic sequence of unlikely chemical reactions
1502 (Hazen 2017), then this view of a mineralogically diverse early Earth provides many
1503 more plausible reactive pathways over a longer timespan than previous models. If,
1504 on the other hand, life is a cosmic imperative that emerges on any mineral- and
1505 water-rich world, then these findings support the hypothesis that life on Earth
1506 emerged rapidly, in concert with a vibrant, diverse Mineral Kingdom, in the earliest
1507 stages of planetary evolution.

1508

1509

ACKNOWLEDGMENTS

1510 This work would not have been possible without the remarkable publication of multi-
1511 volume references, especially *Rock-Forming Minerals* (Deer et al. 1982-2013) and *The*
1512 *Handbook of Mineralogy* (Anthony et al. 1990-2003), as well as ongoing efforts to
1513 develop and expand comprehensive open-access data resources, especially by Jolyon
1514 Ralph, founder of mindat.org, and Robert T. Downs, founder of ruff.info. Collectively,
1515 these mineral informatics pioneers are empowering a new age of data-driven discovery in
1516 mineralogy.

1517 We are deeply grateful to Raquel Alonso Perez, Daniel Hummer, Sergey
1518 Krivovichev, Michael Walter, and Nathan Yee, who provided detailed, thoughtful, and
1519 constructive reviews that significantly improved an early version of this contribution.
1520 George Harlow and Andrea Kozoil contributed comprehensive reviews of the
1521 penultimate manuscript. We are also grateful to Robert Downs, Paul Falkowski, Frank
1522 Hawthorne, Peter Heaney, Jun Korenaga, Jeffrey Post, Simone Runyon, and Steven
1523 Shirey for thoughtful discussions and comments.

1524 This publication is a contribution to the 4D Initiative and the Deep-time Digital Earth
1525 (DDE) program. Studies of mineral evolution and mineral ecology have been supported
1526 by the Alfred P. Sloan Foundation, the W. M. Keck Foundation, the John Templeton
1527 Foundation, NASA Astrobiology Institute (Cycle 8) ENIGMA: Evolution of
1528 Nanomachines In Geospheres and 329 Microbial Ancestors (80NSSC18M0093), a
1529 private foundation, and the Carnegie Institution for Science. Any opinions, findings, or
1530 recommendations expressed herein are those of the authors and do not necessarily reflect
1531 the views of the National Aeronautics and Space Administration.

1532

References

- 1533
1534
1535 Akai, J., Akai, K., Ito, M., Nakano, S., Maki, Y., and Sasagawa, I. (1999) Biologically
1536 induced iron ore at Gunma iron mine, Japan. *American Mineralogist*, 84, 171-182.
- 1537 Alfors, J.T., Stinson, M.C., Matthews, R.A., and Pabst, A. (1965) Seven new barium
1538 minerals from eastern Fresno County, California. *American Mineralogist*, 50, 314-
1539 340.
- 1540 Allwood, A.C., Walter, M.R., Kamber, B.S., Marshall, C.P., and Burch, I.W. (2006)
1541 Stromatolite reef from the Early Archaean era of Australia. *Nature*, 441, 714-718.
- 1542 Anbar, A.D. and Holland, H.D. (1992) The photochemistry of manganese and the origin
1543 of banded iron formations. *Geochimica et Cosmochimica Acta*, 56, 2595-2603.
- 1544 Anbar, A.D., and Knoll, A.H. (2002) Proterozoic ocean chemistry and evolution: A
1545 bioinorganic bridge? *Science*, 297, 1137-1142.
- 1546 Anbar, A. D., Duan, Y., Lyons, T.W., Arnold, G.L., Kendall, B., Creaser, R.A., and
1547 Kaufman, A.J. (2007) A whiff of oxygen before the great oxidation event? *Science*,
1548 317, 1903-1906.
- 1549 Anthony, J.W., Bideaux, R.A., Bladh, K.W., and Nichols, M.C. (1990-2003) Handbook
1550 of Mineralogy, 6 volumes. Mineral Data Publishing.
- 1551 Anthony, J.W., Bideaux, R.A., Bladh, K.W., and Nichols, M.C. (2003) Handbook of
1552 Mineralogy, Volume V. Borates, Carbonates, Sulfates. Mineral Data Publishing.
- 1553 Anzolini, C., Wang, F., Harris, G.A., Locock, A.J., Zhang, D., Nestola, F., Peruzzo, L.,
1554 Jacobsen, S.D., and Pearson, D.G. (2019) Nixonite, Na₂Ti₆O₁₃, a new mineral from a
1555 metasomatized mantle garnet pyroxenite from the western Rae Craton, Darby
1556 kimberlite field, Canada. *American Mineralogist*, 104, 1336-1344.

- 1557 Aparicio, C., and Ginebra, M.-P. (2016) Biomineralization and Biomaterials:
1558 Fundamentals and Applications. Woodhead Publishing.
- 1559 Armstrong, R.L. (1991) The persistent myth of crustal growth. Australian Journal of
1560 Earth Sciences, 38, 613–630.
- 1561 Ashwal, L.D. (1993) Anorthosites. Springer-Verlag.
- 1562 Audra, P., Bosák, P., Gázquez, F., Cailhol, D., Skála, R., Lisá, L., Jonášová, S., Frumkin,
1563 A., Knez, M., Slabe, T., Hajna, N.Z., and Al-Farraj, A. (2017) Bat urea-derived
1564 minerals in arid environment. First identification of allantoin, $C_4H_6N_4O_3$, in Kahf
1565 Kharrat Najem Cave, United Arab Emirates. International Journal of Speleology, 46,
1566 81-92.
- 1567 Audra, P., Waele, J.D., Bentaleb, I., Chronáková, A., Vaclav, K., D'Angeli, I.M.,
1568 Carbone, C., Madonia, G., Vattano, M., Scopelliti, G., Cailhol, D., Vanara, N.,
1569 Temovski, M., Bigot, J.-Y., Nobécourt, J.-C., Galli, E., Rull, F., and Arranz, A.S.
1570 (2018) Guano-related phosphate-rich minerals in European caves. International
1571 Journal of Speleology, 48, 75-105.
- 1572 Augé, T., Cocherie, A., Genna, A., Armstrong, R., Guerrot, C., Mukherjee, M.M., and
1573 Patra, R.N. (1993) Age of the Baula PGE mineralization (Orissa, India) and its
1574 implications concerning the Singhbhum Archaean nucleus. Precambrian Research,
1575 121, 85-101.
- 1576 Bai, W.J., Zhou, M.F., and Robinson, P.T. (2011) Possibly diamond-bearing mantle
1577 peridotites and chromites in the Luobusa and Dongqiao ophiolites, Tibet. Canadian
1578 Journal of Earth Sciences, 30, 1650-1659.

- 1579 Baker, G. (1962) Detrital Heavy Minerals in Natural Accumulates with Special
1580 Reference to Australian Occurrences. Australia Institute of Mining and Metallurgy.
- 1581 Banerjee, D.M. (1971) Precambrian stromatolitic phosphorites of Udaipur, Rajasthan,
1582 India, GSA Bulletin, 82, 2319-2329.
- 1583 Barboni, M., Boehnke, P., Keller, B., Kohl, I.E., Schoene, B., Young, E.D., and
1584 McKeegan, K.D., (2017) Early formation of the Moon 4.51 billion years ago. Science
1585 Advances, 3, e1602365.
- 1586 Barker, W.W., Welch, S.A., and Banfield, J.F. (1998) Experimental observations of the
1587 effects of bacteria on aluminosilicate weathering. American Mineralogist, 83, 1551-
1588 1563.
- 1589 Barley, M.E., and Groves, D.I. (1992) Supercontinent cycles and the distribution of metal
1590 deposits through time. Geology, 20, 291-294.
- 1591 Barnes, H.L., and Rose, A.W. (1998) Origins of hydrothermal ores. Science, 279, 2064-
1592 2065.
- 1593 Barturin, G.N., and Bezrukov, P.L. (1979) Phosphorites on the sea floor and their origin.
1594 Marine Geology, 31, 317-332.
- 1595 Beazley, M.J., Matrinez, R.J., Sobecky, P.A., Webb, S.M., and Taillefert, M. (2017)
1596 Uranium biomineralization as a result of bacterial phosphatase activity: Insights from
1597 bacterial isolates from a contaminated subsurface. Environmental Science and
1598 Technology, 41, 5701-5707.
- 1599 Behrensmeyer, A.K., Kidwell, S.M., and Gastaldo, R.A. (2000) Taphonomy and
1600 paleobiology. Paleobiology, 26, 103-147.

- 1601 Bekker, A., Slack, J.F., Planavsky, N., Krapež, B., Hofmann, A., Konhauser, K.O., and
1602 Rouxel, O.J. (2010) Iron formation: the sedimentary product of a complex interplay
1603 among mantle, tectonic, oceanic, and biospheric process. *Economic Geology*, 105,
1604 467–508.
- 1605 Bell, K. (1989) *Carbonatites: Genesis and Evolution*. Unwin Hyman.
- 1606 Belousova, E.A., Kostitsyn, Y.A., Griffin, W.L., Begg, G.C., O'Reilly, S.Y., and
1607 Pearson, N.J. (2010) The growth of the continental crust: Constraints from zircon Hf-
1608 isotope data. *Lithos*, 119, 457–466.
- 1609 Berg, J.S., Schwedt, A., Kreuzmann, A.-C., Kuypers, M.M.M., and Milucka, J. (2014)
1610 Polysulfides as intermediates in the oxidation of sulfide to sulfate by *Beggiatoa*
1611 *spp.* *Applied Environmental Microbiology*, 80, 629–636.
- 1612 Berg, J.S., Duverger, A., Cordier, L., Laberty-Robert, C., Guyot, F., and Miot, J. (2020)
1613 Rapid pyritization in the presence of a sulfur/sulfate-reducing bacterial consortium.
1614 *Scientific Reports*, 10, Article 8264.
- 1615 Bischoff, A. (1998) Aqueous alteration of carbonaceous chondrites: Evidence for
1616 preaccretionary alteration – A review. *Meteoritics & Planetary Science*, 33, 1113-
1617 1122.
- 1618 Blais, S., and Auvray, B. (1990) Serpentinization in the Archean komatiitic rocks of the
1619 Kuhmo greenstone belt, eastern Finland. *Canadian Mineralogist*, 28, 55-66.
- 1620 Blichert-Toft, J., Moynier, F., Lee, C.A., Telouk, P., and Albare`de, F. (2010) The early
1621 formation of the IV iron meteorite parent body. *Earth and Planetary Science Letters*,
1622 296, 469–480.

- 1623 Blöthe, M., Wegorzewski, A., Müller, C., Simon, F., Kuhn, T., and Schippers, A. (2015)
1624 Manganese-cycling microbial communities inside deep-sea manganese
1625 nodules. *Environmental Science and Technology*, 49, 7692–7700.
- 1626 Bodiselitsch, B., Koeberl, C., Master, S., and Reimold, W.U. (2005) Estimating duration
1627 and intensity of Neoproterozoic snowball glaciations from Ir anomalies. *Science*, 308,
1628 239-242.
- 1629 Boggs, S. Jr. (2006) *Principles of Sedimentology and Stratigraphy*, Fourth Edition.
1630 Pearson Education.
- 1631 Boujibar, A., Howell, S., Zhang, S., Hystad, G., Prabhu, A., Liu, N., Stephan, T., Narkar,
1632 S., Eleish, A., Morrison, S.M., Hazen, R.M., and Nittler, L.R. (2020) Cluster analysis
1633 of presolar silicon carbide grains: Evaluation of their classification and astrophysical
1634 implications. *Astrophysical Journal Letters*, 907, L39 (14 pp.).
- 1635 Bowles, J.F.W., Howie, R.A., Vaughan, D.J., and Zussman, J. (2011) *Rock-Forming*
1636 *Minerals. Volume 5A. Second Edition. Non-Silicate: Oxides, Hydroxides and*
1637 *Sulphides*. Geological Society of London.
- 1638 Boyd, R. (1991) Realism, anti-foundationalism and the enthusiasm for natural kinds.
1639 *Philosophical Studies*, 61, 127-148.
- 1640 Boyd, R. (1999) Homeostasis, species, and higher taxa. In R. Wilson [Editor], *Species:*
1641 *New Interdisciplinary Essays*. Cambridge, Massachusetts: Cambridge University
1642 Press, pp. 141-186.
- 1643 Boyd, E.S., and Druschel, G.K. (2013) Involvement of intermediate sulfur species in
1644 biological reduction of elemental sulfur under acidic, hydrothermal
1645 conditions. *Applied Environmental Microbiology*, 79, 2061–2068.

- 1646 Bradley, D.C. (2011) Secular trends in the geologic record and the supercontinent cycle.
1647 Earth-Science Review, 108, 16-33.
- 1648 Brasier, M.D. (1998) A billion years of environmental stability and the emergence of
1649 eukaryotes: New data from northern Australia. *Geology*, 26, 555-558.
- 1650 Brasier, M. (2012) *Secret Chambers: The Inside Story of Cells and Complex Life*. Oxford
1651 University Press.
- 1652 Brearley, A.J. and Jones, R.H. (1998) Chondritic meteorites. In J.J. Papike, Ed., *Planetary*
1653 *Materials. Reviews in Mineralogy and Geochemistry*, 36, 3.1-3.398.
- 1654 Brown, M. (2007) Metamorphic conditions in orogenic belts: a record of secular change.
1655 *International Geology Review*, 49, 193–234.
- 1656 Brown, M., Johnson, T., and Gardiner, N.J. (2020) Plate tectonics and the Archean Earth.
1657 *Annual Review of Earth and Planetary Sciences*, 48, 291–320.
- 1658 Buick, R. and Dunlop, J.S.R. (1990) Evaporitic sediments of early Archaean age from the
1659 Warrawoona Group, North Pole, Western Australia. *Sedimentology*, 37, 247-277.
- 1660 Buick, R., Des Marais, D.J., and Knoll, A.H. (1995) Stable isotopic compositions of
1661 carbonates from the Mesoproterozoic Bangemall group, northwestern Australia.
1662 *Chemical Geology*, 123, 153-171.
- 1663 Burke, E.A.J. (2006) The end of CNMMN and CCM—Long live the CNMNC!
1664 *Elements*, 2, 388.
- 1665 Burnett, W.C. and Riggs, S.R., Eds. (1990) *Phosphate Deposits of the World: Vol. 3,*
1666 *Genesis of Neogene to Recent Phosphorites*. Cambridge University Press.

- 1667 Button, A. (1982) Sedimentary iron deposits, evaporates and phosphorites: State of the
1668 art report. In H.D. Holland and M. Schidlowski, Eds., Mineral Deposits and the
1669 Evolution of the Biosphere. Springer-Verlag, pp. 259-273.
- 1670 Cairncross, B., and Beukes, N.J. (2013) The Kalahari Manganese Field, the Adventure
1671 Continues. Struik Nature Publishers.
- 1672 Cámara, F., Ciriotti, M.E., Bittarello, E., Nestola, F., Massimi, F., Radica, F., Costa, E.,
1673 Benna, P., and Piccoli, G.C. (2014) Arsenic-bearing new mineral species from Valletta
1674 mine, Maira Valley, Piedmont, Italy: I. Grandaite, $\text{Sr}_2\text{Al}(\text{AsO}_4)_2(\text{OH})$, description and
1675 crystal structure. Mineralogical Magazine, 78, 757-774.
- 1676 Canfield, D. (2014) Oxygen: A Four Billion Year History. Princeton University Press.
- 1677 Carmichael, S.K., and Bräuer, S.L. (2015) Microbial diversity and manganese cycling: A
1678 review Cave Systems. Life in Extreme Environments. De Gruyter, pp. 137-160.
- 1679 Carpentier, W., Sandra, K., De Smet, I., Brigé, A., De Smit, L., and Van Neeumen, J.
1680 (2003) Microbial reduction and precipitation of vanadium by *Shewanella oneidensis*.
1681 Applied and Environmental Microbiology, June 2003, 3636-3639.
- 1682 Catheart, R.B. (2011) Anthropoc rock: a brief history. History of Geo- and Space Science,
1683 2, 57-74.
- 1684 Cavarretta, G., Mottana, A., and Trece, F. (1981) Cesanite, $[\text{Ca}_2\text{Na}_3[(\text{OH})(\text{SO}_4)_3]]$, a
1685 sulphate isotypic to apatite, from the Cesano geothermal field (Latium, Italy).
1686 Mineralogical Magazine 44, 269-273
- 1687 Cawood, P.A., and Hawkesworth, C.J. (2015) Temporal relations between mineral
1688 deposits and global tectonic cycles. Geological Society of London Special
1689 Publications, 393, 9-21.

- 1690 Cawood, P.A., Hawkesworth, C.J., and Dhuime, B. (2013) The continental record and the
1691 generation of continental crust. *GSA Bulletin*, 125, 14-32.
- 1692 Cawood, P.A., Hawkesworth, C.J., Pisarevsky, S.A., Dhuime, B., Capitanio, F.A., and
1693 Nebel, O. (2018) Geological archive of the onset of plate tectonics. *Philosophical*
1694 *Transactions of the Royal Society*, A376, 20170405.
- 1695 Černý, P. (2005) The Tanco rare-element pegmatite deposit, Manitoba: Regional context,
1696 internal anatomy, and global comparisons. In R.L. Linnen and I.M. Samson [Eds.],
1697 Rare-element geochemistry and mineral deposits. Geological Association of Canada
1698 Short Course, 127-158.
- 1699 Chan, M.A., Hinman, N.W., Potter-McIntyre, S.L., Schubert, K.E., Gillams, R.J.,
1700 Awramik, S.M., Boston, P.J., Bower, D.M., Des Marais, D.J., Farmer, J.D., Jia, T.Z.,
1701 King, P.L., Hazen, R.M., Leveille, R.J., Papineau, D., Rempfert, K.R., Sanchez-
1702 Roman, M., Spear, J.R., Southam, G., Stern, J.C., and Cleaves, H.J. II (2019)
1703 Deciphering biosignatures in planetary contexts. *Astrobiology*, 19, 28 p.
- 1704 Chang, L.L.Y., Howie, R.A., and Zussman, J. (1996) *Rock-Forming Minerals. Volume*
1705 *5B. Non-silicates. Sulphates, Carbonates, Phosphates and Halides. Second Edition.*
1706 Longman Group.
- 1707 Chang, S.-B.R. ,and Kirschvink, J.L. (1989) Magnetofossils, the magnetization of
1708 sediments, and the evolution of magnetite biomineralization. *Annual Review of Earth*
1709 *and Planetary Sciences*, 17, 169-195.
- 1710 Chappell, B.W., and White, A.J.R. (2001) Two contrasting granite types: 25 years later.
1711 *Australian Journal of Earth Sciences*, 48, 489-499.

- 1712 Chauhan, D.S. (1979) Phosphate-bearing stromatolites of the Precambrian Aravalli
1713 phosphorite deposits of the Udaipur region, their environmental significance and
1714 genesis of phosphorite. *Precambrian Research*, 8, 95-126.
- 1715 Chopin, C. (1984) Coesite and pure pyrope in high-grade blueschists of the western Alps:
1716 a first record and some consequences. *Contributions to Mineralogy and Petrology*, 86,
1717 107–118.
- 1718 Ciesla, F.J., Lauretta, D.S., Cohen, B.A., and Hood, L.L. (2003) A nebular origin for
1719 chondritic fine-grained phyllosilicates. *Science*, 299, 549-552.
- 1720 Cleland, C.E., Hazen, R.M., and Morrison, S.M. (2020) Historical natural kinds and
1721 mineralogy: Systematizing contingency in the context of necessity. *Proceedings of the*
1722 *National Academy of Sciences*, 118, e2015370118 (8 pp.).
- 1723 Coker, V.S., Bell, A.M.T., Pearce, C.I., Patrick, R.A.D., van der Laan, G., and Lloyd,
1724 J.R. (2008) Time-resolved synchrotron powder X-ray diffraction study of magnetite
1725 formation by an Fe(III)-reducing bacterium *Geobacter sulfurreducens*. *American*
1726 *Mineralogist*, 93, 540-547.
- 1727 Condie, K.C., and Pease, V. [Eds] (2008) *When Did Plate Tectonics Start on Earth?*
1728 *Geological Society of America Special Paper*, 440.
- 1729 Cook, P.J., and Shergold, J.H. (1990) *Phosphate Deposits of the World. Volume 1,*
1730 *Proterozoic and Cambrian Phosphorites*. Cambridge University Press.
- 1731 Corcoran, P.L., Moore, C.J., and Jazvac, K. (2014) An anthropogenic marker horizon in
1732 the future rock record. *GSA Today*, 24, 4-8.
- 1733 Craig, J.R., and Vaughan, D.J. (1994) *Ore microscopy and ore petrography*. Wiley.

- 1734 Crevello, P.D., Wilson, J.L., Sarg, J.F., and Read, J.F. [Editors] (1989) Controls on
1735 Carbonate Platform and Basin Development. SEPM Special Publication, 44.
- 1736 Cron, B., Henri, P., Chan, C.S., Macalady, J.L., and Cosmidis, J. (2019) Elemental sulfur
1737 formation by *Sulfuricurvum kujiense* is mediated by extracellular organic compounds.
1738 *Frontiers in Microbiology*, 10, Article 2710.
- 1739 Debaille, V., O'Neill, C., Brandon, A.D., Haenecour, P., Yin, Q.-Z., Mattielli, N., and
1740 Treiman, A.H. (2013) Stagnant-lid tectonics in early Earth revealed by ¹⁴²Nd
1741 variations in late Archean rocks. *Earth and Planetary Science Letters*, 373, 83–92.
- 1742 Deer, W.A., Howie, R.A., and Zussman, J. (1982-2013) *Rock-Forming Minerals*, second
1743 edition, 11 volumes. Wiley.
- 1744 Deer, W.A., Howie, R.A., Wise, W.S., and Zussman, J. (2004) *Rock-Forming Minerals*.
1745 Volume 4B, second edition. *Framework Silicates: Silica Minerals, Feldspathoids and*
1746 *the Zeolites*. Wiley.
- 1747 Delaney, M.L. (1998) Phosphorus accumulation in marine sediments and oceanic
1748 phosphorus cycle. *Biogeochemical Cycles*, 12, 563–572.
- 1749 Dhuime, B., Hawkesworth, C.J., Cawood, P.A., and Storey, C.D. (2012) A change in the
1750 geodynamics of continental growth 3 billion years ago. *Science*, 335, 1334–1336.
- 1751 Dick, H.J.B. (1989) Abyssal peridotites, very slow spreading ridges and ocean ridge
1752 magmatism. Geological Society, London, *Special Publications*, 42, 71–105.
- 1753 Dilek, Y. (2003) Ophiolite pulses, orogeny, and mantle plumes. Geological Society of
1754 London *Special Publications*, 218, 9-19.

- 1755 Dong, J., Fischer, R.A., Stixrude, L.P., and Lithgow-Bertelloni, C.R. (2021) Constraining
1756 the volume of Earth's early oceans with a temperature-dependent mantle water storage
1757 capacity model. *AGU Advances*, 2, e2020AV000323.
- 1758 Douglas, S., and Yang, H. (2002) Mineral biosignatures in evaporites: presence of
1759 rosickyite in an endoevaporitic microbial community from Death Valley,
1760 California. *Geology*, 30, 1075–1078.
- 1761 Dove, P.M. (2010) The rise of skeletal biomineralization. *Elements*, 6, 37-42.
- 1762 Dove, P.M., De Yore, J.J., and Weiner, S. [Editors] (2003) Biomineralization. *Reviews in*
1763 *Mineralogy and Geochemistry*, 54. Mineralogical Society of America.
- 1764 Downes, H., Wall, F., Demy, A., and Szabo, C. (2012) Continuing the carbonatite
1765 controversy. *Mineralogical Magazine*, 76, 255-257.
- 1766 Dumitrașcu, D., Acalovschi, M., Marza, I., and Suciu, A. (1984) Gallstones –
1767 mineralogical and chemical investigations. *La Revue de Medecine Interne*, 22, 209-
1768 212.
- 1769 Ebel, D.S., and Kamilli, R.J. (2018) Paragenesis. In: White W.M., Ed., *Encyclopedia*
1770 *of Geochemistry*. Encyclopedia of Earth Sciences Series. Springer.
- 1771 Eiler, J.M. (2007) On the origin of granites. *Science*, 315, 951-952.
- 1772 El Goresy, A., Zinner, E., Matsunami, S., Palme, H., Spettel, B., Lin, Y., and Nazarov,
1773 M. (2002) Efremovka 101.1: A CAI with ultra-refractory REE patterns and enormous
1774 enrichments of Sc, Zr, and Y in fassaite and perovskite. *Geochimica et Cosmochimica*
1775 *Acta*, 66, 1459–1491.
- 1776 Elkins-Tanton, L.T. (2011) Formation of early water oceans on rocky planets.
1777 *Astrophysics and Space Science*, 332, 359–364.

- 1778 Endo, K. (1962) A mineralogical investigation of gall stone. Tohoku Journal of
1779 Experimental Medicine, 76, 326-349.
- 1780 Endo, K., Kogure, T., and Nagasawa, H. (2018) Biomineralization: From Molecular and
1781 Nano-structural Analyses to Environmental Science. Springer.
- 1782 Ensikat, H.-J., Geisler, T., and Weigend, M. (2016) A first report of hydroxylated apatite
1783 as structural biomineral in *Loasaceae* – plant’s teeth against herbivores. Scientific
1784 Reports, 6 Article 26073.
- 1785 Ereshefsky, M. (2014) Species, historicity, and path dependency. Philosophy of Science,
1786 81, 714-726.
- 1787 Ernst, R.E. (2014) Large Igneous Provinces. Cambridge University Press.
- 1788 Essene, E.J., and Fisher, D.C. (1986) Lightning strike fusion: Extreme reduction and
1789 metal-silicate immiscibility. Science, 234, 189-193.
- 1790 Falkowski, P., Scholes, R.J., Boyle, E., Canadell, J., Canfield, D., Elser, J., Gruber, N.,
1791 Hibbard, K., Högberg, P., Linder, S., Mackenzie, F.T., Moore, B. III, Pederson, T.,
1792 Rosenthal, Y., Seitzinger, S., Smetacek, V., and Steffen, W. (2000) The global carbon
1793 cycle: A test of our knowledge of Earth as a system. Science, 290, 291-296.
- 1794 Farquhar, J., Bao, H., and Thiemens, M.H. (2000) Atmospheric influence of Earth's
1795 earliest sulfur cycle. Science, 289, 756-758.
- 1796 Farquhar, J., Savarino, I., Airieau, S., and Thiemens, M.H. (2001) Observations of
1797 wavelength-sensitive, mass-independent sulfur isotope effects during SO₂ photolysis:
1798 Implications for the early atmosphere. Journal of Geophysical Research, 106, 1-11.

- 1799 Farquhar, J., Peters, M., Johnston, D.T., Strauss, H., Masterson, A., Wiechert, U., and
1800 Kaufman, A.J. (2007) Isotopic evidence for Mesoarchean anoxia and changing
1801 atmospheric sulphur chemistry, *Nature*, 449, 706-709.
- 1802 Fayek, M.J., Utsunomiya, S., Pfiffner, S.M., Anovitz, L.M., White, D.C., Riciputi, L.R.,
1803 Ewing, R.C., and Stadermann, F.J. (2005) Nanoscale chemical and isotopic
1804 characterization of *Geobacter sulfurreducens* surfaces and bio-precipitated uranium
1805 minerals. *Canadian Mineralogist*, 43, 1631-1641.
- 1806 Fike, D.A., Grotzinger, J.P., Pratt, L.M., and Summons, R.E. (2006) Oxidation of the
1807 Ediacaran ocean. *Nature*, 444, 744–747.
- 1808 Finch, R.J., and Murakami, T. (1999) Systematics and paragenesis of uranium minerals.
1809 *Reviews in Mineralogy*, 38, 91-180.
- 1810 Frankel, R.B., and Bazylinski, D.A. (2003) Biologically induced mineralization by
1811 bacteria. In P.M. Dove, J.J. DeYoreo and S. Weiner, Eds., *Biom mineralization. Reviews*
1812 *in Mineralogy and Geochemistry*, 54, 95-114.
- 1813 Frondel, C. (1958) *Systematic Mineralogy of Uranium and Thorium*. United States
1814 Geological Survey Bulletin, 1064, 400 p.
- 1815 Furnes, H., de Witt, M., Staudigel, H., Rosing, M., and Muehlenbachs, K. (2007) A
1816 vestige of Earth's oldest ophiolite. *Science*, 315, 1704-1707.
- 1817 Galezowski, L., Recham, N., Larcher, D., Miot, J., Skouri-Panet, F., and Guyot, F. (2020)
1818 Microbially induced mineralization of layered Mn oxides electroactive in Li batteries.
1819 *Frontiers in Microbiology*, 11, Article 2031.
- 1820 Garvie, L.A.J. (2003) Decay-induced biomineralization of saguaro cactus (*Carnegiea*
1821 *gigantea*). *American Mineralogist*, 88, 1879-1888.

- 1822 Giannossi, M.L., Mongelli, G., and Summa, V. (2009) The mineralogy and internal
1823 structure of kidney stones. *NDT Plus*, 2, 418-419.
- 1824 Gibb, E.L., Whittet, D.C.B., Boogert, A.C.A., and Tielens, A.G.G.M. (2004) Interstellar
1825 ice: The Infrared Space Observatory legacy. *The Astrophysical Journal Supplement*
1826 *Series*, 151, 35-73.
- 1827 Gleeson, D.F., Williamson, C., Grasby, S.E., Pappalardo, R.T., Spear, J.R., and
1828 Templeton, A.S. (2011) Low temperature S⁰ biomineralization at a supraglacial spring
1829 system in the Canadian high Arctic. *Geobiology*, 9, 360–375.
- 1830 Godman, M. (2019) Scientific realism with historical essences: The case of species.
1831 *Synthese* <https://doi.org/10.1007/s11229-018-02034-3>
- 1832 Golden, J.J. (2020) Mineral evolution database: Data model for mineral age associations.
1833 MS Thesis, Department of Geosciences, University of Arizona.
- 1834 Golden, J.J., Pires, A.J., Hazen, R.M., Downs, R.T., Ralph, J., and Meyer, M. (2016)
1835 Building the Mineral evolution database: implications for future big data
1836 analysis. *Proceedings of the Geological Society of America Annual Meeting Abstracts*
1837 *with Programs*. doi: 10.1130/abs/2016AM-286024
- 1838 Goldfarb, R.J., Groves, D.I., and Gardoll, S. (2001) Orogenic gold and geologic time: a
1839 global synthesis. *Ore Geology Reviews*, 18, 1-75.
- 1840 Grapes, R. (2005) *Pyrometamorphism*. Second Edition. Springer.
- 1841 Greber, N.D., Dauphas, N., Bekker, A., Ptacek, M.P., Bindeman, I.N., and Hofmann, A.
1842 (2017) Titanium isotopic evidence for felsic crust and plate tectonics 3.5 billion years
1843 ago. *Science*, 357, 1271–1274.

- 1844 Greenberg, J.M. (1991) Interstellar dust-gas relationships. In M.M. Shapiro, R.
1845 Silberberg, and J.P. Wefel, Eds., Cosmic Rays, Supernovae, and the Interstellar
1846 Medium. NATO ASI Series: Mathematical and Physical Sciences, 120, 57-68.
- 1847 Grew, E.S., and Hazen, R.M. (2014) Beryllium mineral evolution. American
1848 Mineralogist, 99, 999-1021.
- 1849 Grew, E.S., Bada, J.L., and Hazen, R.M. (2011) Borate minerals and the origin of the
1850 RNA world. *Origins of Life and Evolution of the Biosphere*, 41, 307-316.
- 1851 Grew, E.S., Dymek, R.F., De Hoog, J.C.M., Harley, S.L., Boak, J.M., Hazen, R.M., and
1852 Yates, M.G. (2015) Boron isotopes in tourmaline from the 3.7-3.8 Ga Isua Belt,
1853 Greenland: Sources for boron in Eoarchean continental crust and seawater.
1854 *Geochimica et Cosmochimica Acta*, 163, 156-177.
- 1855 Grew, E.S., Krivovichev, S.V., Hazen, R.M., and Hystad, G. (2016) Evolution of
1856 structural complexity in boron minerals. *Canadian Mineralogist*, 54, 125-143.
- 1857 Grew, E.S., Hystad, G., Hazen, R.M., Golden, J., Krivovichev, S.V., and Gorelova, L.A.
1858 (2017) How many boron minerals occur in Earth's upper crust? *American*
1859 *Mineralogist*, 102, 1573-1587.
- 1860 Grew, E.S., Hystad, G., Toapanta, M., Eleish, A., Ostroverkhova, A., Golden, J., and
1861 Hazen, R.M. (2019) Lithium mineral evolution and ecology: Comparison with boron
1862 and beryllium. *European Journal of Mineralogy*, 31, 755-774.
- 1863 Gross, S. (1977): *The Mineralogy of the Hatrurim Formation, Israel*. Geological Survey
1864 of Israel, Bulletin no. 70, 80 pp.

- 1865 Grotzinger, J.P., and Knoll, A.H. (1999) Stromatolites in Precambrian carbonates:
1866 Evolutionary mileposts or environmental dipsticks. *Annual Review of Earth and*
1867 *Planetary Sciences*, 27, 313-358.
- 1868 Groves, D.I., and Bierlein, F.P. (2007) Geodynamic settings of mineral deposit systems.
1869 *Journal of the Geological Society of London*, 164, 19-30.
- 1870 Groves, D.I., Vielreicher, R.M., Goldfarb, R.J., and Condie, K.C. (2005) Controls on the
1871 heterogeneous distribution of mineral deposits through time. *Geological Society of*
1872 *London Special Publications*, 248, 71-101.
- 1873 Groves, D.I., Bierlein, F.P., Meinert, L.D., and Hitzman, M.W. (2010) Iron oxide copper-
1874 gold (IOCG) deposits through Earth history: Implications for origin, lithospheric
1875 setting, and distinction from other epigenetic iron oxide deposits. *Economic Geology*,
1876 105, 641-654.
- 1877 Guilbert, J.M., and Park, C.F., Jr. (2007) *The Geology of Ore Deposits*. Waveland Press.
- 1878 Genceli Güner, F.E., Sakurai, T., and Hondoh, T. (2013) Ernstburkeite.
1879 $\text{Mg}(\text{CH}_3\text{SO}_3)_2 \cdot 12\text{H}_2\text{O}$, a new mineral from Antarctica. *European Journal of*
1880 *Mineralogy*, 25, 79-84.
- 1881 Gross, S. (1977) *The Mineralogy of the Hatrurim Formation, Israel*. Geological Survey of
1882 Israel, Bulletin no. 70, 80 pp.
- 1883 Guo, M., and Korenaga, J. (2020) Argon constraints on the early growth of felsic
1884 continental crust. *Science Advances*, 6, eaaz6234.
- 1885 Hacker, B.R. (2006) Pressures and temperatures of ultrahigh-pressure metamorphism:
1886 Implications for UHP tectonics and H_2O in subducting slabs. *International Geology*
1887 *Review*, 48, 1053-1066.

- 1888 Harlow, D.E., and Austrheim, H. (2013) Metasomatism and the Chemical Transformation
1889 of Rock: Rock-Mineral-Fluid Interactions in Terrestrial and Extraterrestrial
1890 Environments. Springer-Verlag.
- 1891 Hatert, F., Mills, S.J., Hawthorne, F.C., and Rumsey, M.S. (2021) A comment on “An
1892 evolutionary system of mineralogy: Proposal for a classification of planetary materials
1893 based on natural kind clustering.” American Mineralogist, 106, 150-153.
- 1894 Hawley, K., and Bird, A. (2011) What are natural kinds? Philosophical Perspectives, 25,
1895 205-221.
- 1896 Haymon, R.M., and Kastner, M. (1981) Hot spring deposits on the East Pacific Rise at
1897 21°N: Preliminary description of mineralogy and genesis. Earth and Planetary Science
1898 Letters, 53, 363-381.
- 1899 Hazen, R.M. (2013) Paleomineralogy of the Hadean Eon: A preliminary list. American
1900 Journal of Science, 313, 807-843.
- 1901 Hazen, R.M. (2014) Data-driven abductive discovery in mineralogy. American
1902 Mineralogist, 99, 2165-2170.
- 1903 Hazen, R.M. (2015) Mineral evolution, the Great Oxidation Event, and the rise of
1904 colorful minerals. Mineralogical Record, 46, 805-816, 834.
- 1905 Hazen, R.M. (2017) Chance, necessity, and the origins of life: A physical sciences
1906 perspective. Philosophical Transactions of the Royal Society, A375, 20160353.
- 1907 Hazen, R.M. (2018) Titan mineralogy: Insights on organic mineral evolution. American
1908 Mineralogist, 103, 341-342.
- 1909 Hazen, R.M. (2019) An evolutionary system of mineralogy: Proposal for a classification
1910 based on natural kind clustering. American Mineralogist, 104, 810-816.

- 1911 Hazen, R.M. (2021) Reply to “Comment on ‘An evolutionary system of mineralogy:
1912 Proposal for a classification based on natural kind clustering’.” American
1913 Mineralogist, 106, 154-156.
- 1914 Hazen, R.M., and Ausubel, J.H. (2016) On the nature and significance of rarity in
1915 mineralogy. American Mineralogist, 101, 1245-1251.
- 1916 Hazen, R.M., and Morrison, S.M. (2020) An evolutionary system of mineralogy, Part I:
1917 stellar mineralogy (>13 to 4.6 Ga). American Mineralogist, 105, 627-651.
- 1918 Hazen, R.M., and Morrison, S.M. (2021) An evolutionary system of mineralogy, Part V:
1919 Aqueous and thermal alteration of planetesimals (4.565 to 4.550 Ga). American
1920 Mineralogist, in press.
- 1921 Hazen, R.M., and Zalaziewski, J. (2019) 2.1 Rock components—Synthetic mineral-like
1922 compounds. In: J. Zalaziewski, C.N. Waters, M. Williams, and C. Summerhayes, Eds.,
1923 The Anthropocene as a Geologic Unit. Cambridge University Press, pp.42-46.
- 1924 Hazen, R.M., Papineau, D., Bleeker, W., Downs, R.T., Ferry, J.M., McCoy, T.L.,
1925 Sverjensky, D.A., and Yang, H. (2008) Mineral evolution. American Mineralogist, 93,
1926 1693-1720.
- 1927 Hazen, R.M., Ewing, R.J., and Sverjensky, D.A. (2009) Evolution of uranium and
1928 thorium minerals. American Mineralogist, 94. 1293-1311.
- 1929 Hazen, R.M., Golden, J.J., Downs, R.T., Hysted, G., Grew, E.S., Azzolini, D., and
1930 Sverjensky, D.A. (2012) Mercury (Hg) mineral evolution: A mineralogical record of
1931 supercontinent assembly, changing ocean geochemistry, and the emerging terrestrial
1932 biosphere. American Mineralogist, 97, 1013-1042.

- 1933 Hazen, R.M., Liu, X.-M., Downs, R.T., Golden, J.J., Pires, A.J., Grew, E.S., Hystad, G.,
1934 Estrada, C., and Sverjensky, D.A. (2014) Mineral evolution: Episodic metallogenesis,
1935 the supercontinent cycle, and the coevolving geosphere and biosphere. Society of
1936 Economic Geologists Special Publication, 18, 1-15.
- 1937 Hazen, R.M., Grew, E.S., Downs, R.T., Golden, J., and Hystad, G. (2015) Mineral
1938 ecology: Chance and necessity in the mineral diversity of terrestrial planets. Canadian
1939 Mineralogist, 53, 295-323.
- 1940 Hazen, R.M., Grew, E.S., Origlieri, M., and Downs, R.T. (2017) On the mineralogy of the
1941 “Anthropocene Epoch.” American Mineralogist, 102, 595-611.
- 1942 Hazen, R.M., Downs, R.T., Elesish, A., Fox, P., Gagné, O., Golden, J.J., Grew, E.S.,
1943 Hummer, D.R., Hystad, G., Krivovichev, S.V., Li, C., Liu, C., Ma, X., Morrison,
1944 S.M., Pan, F., Pires, A.J., Prabhu, A., Ralph, J., Runyon, S.E., and Zhong, H. (2019)
1945 Data-driven discovery in mineralogy: Recent advances in data resources, analysis, and
1946 visualization. China Engineering, 5, 397-405.
- 1947 Hazen, R.M., Morrison, S.M., and Prabhu, A. (2021) An evolutionary system of
1948 mineralogy, Part III: Primary chondrule mineralogy (4.566 to 4.561 Ga). American
1949 Mineralogist, 106, 325-350.
- 1950 Heaman, L.W., Phillips, D., and Pearson, D.G. (2019) Dating kimberlites: Methods and
1951 emplacement patterns through time. Elements, 15, 399-406.
- 1952 Heck, P.R., Greer, J., Kööp, L., Trappitsch, R., Gyngard, F., Busemann, H., Maden, C.,
1953 Ávila, J.N., Davis, A.M., and Wieler, R. (2020) Lifetimes of interstellar dust from
1954 cosmic ray exposure ages of presolar grains. Proceedings of the National Academy of
1955 Sciences USA, Jan. 13, 2020, DOI: 10.1073/pnas.1904573117

- 1956 Heinrich, C.A., and Henley, R.W. (1989) Hydrothermal Systems. Australian Mineral
1957 Foundation.
- 1958 Hekinian, R., Fevrier, M., Bischoff, J.L., Picot, P., and Shanks, W.C. (1980) Sulfide
1959 deposits from the East Pacific Rise near 21 N. *Science*, 207, 1433-1444.
- 1960 Helgren, D.M., and Butzer, K.W. (1977) Paleosols of the Southern Cape Coast, South
1961 Africa: Implications for laterite definition, genesis, and age. *Geographical Review*, 67,
1962 430–445.
- 1963 Hess, B.L., Piazzolo, S., and Harvey, J. (2021) Lightning strikes as a major facilitator of
1964 prebiotic phosphorus reduction on early Earth. *Nature Communications*, 12, Article
1965 #1535.
- 1966 Hill, C., and Forti, P. (1997) *Cave Minerals of the World*. Second Edition. National
1967 Speleological Society.
- 1968 Hill, I.G., Worden, R.H., and Meighan, I.G. (2000) Geochemical evolution of a
1969 palaeolaterite: the Interbasaltic Formation, Northern Ireland. *Chemical Geology*, 166,
1970 65–84.
- 1971 Hlawatsch, S., Neumann, T., van den Berg, C.M.G., Kersten, M., Hari, J., and Suess, E.
1972 (2002) Fast-growing, shallow-water ferro-manganese nodules from the western Baltic
1973 Sea: origin and modes of trace element incorporation. *Marine Geology*, 182, 373–387.
- 1974 Hoffman, P.F., Kaufman, A.J., Halverson, G.P., and Schrag, D.P. (1998) A
1975 Neoproterozoic snowball Earth. *Science*, 281, 1342-1346.
- 1976 Holland, H.D. (1984) *The Chemical Evolution of the Atmosphere and Oceans*. Princeton
1977 University Press.

- 1978 Holland, H.D., and Rye, R. (1997) Evidence in pre-2.2 Ga Paleosols for the early
1979 evolution of atmospheric oxygen and terrestrial biota; discussion and reply. *Geology*,
1980 25, 857-859.
- 1981 Holm, N.G., Oze, C., Mousis, O., Waite, J.H., and Guilbert-Lepoutre, A. (2015)
1982 Serpentinization and the formation of H₂ and CH₄ on celestial bodies (planets, moons,
1983 comets). *Astrobiology*, 2015, 587-600.
- 1984 Hopkins, M., Harrison, T.M., and Manning, C.E. (2008) Low heat flow inferred from >4
1985 Gyr zircons suggest Hadean plate boundary interactions. *Nature*, 456, 493–496.
- 1986 Huston, D.L., Pehrsson, S., Eglington, B.M., and Zaw, K. (2010) The geology and
1987 metallogeny of volcanic-hosted massive sulfide deposits: Variations through geologic
1988 time and with tectonic setting. *Economic Geology*, 105, 571-591.
- 1989 Hystad, G., Downs, R.T., and Hazen, R.M. (2015) Mineral frequency distribution data
1990 conform to a LNRE model: Prediction of Earth’s “missing” minerals. *Mathematical*
1991 *Geosciences*, 47, 647-661.
- 1992 Ishibashi, J.-I., Okino, K., and Sunamura, M. [Eds] (2015) *Subseafloor Biosphere Linked*
1993 *to Hydrothermal Systems*. Springer.
- 1994 Isley, A.E., and Abbott, D.H. (1999) Plume-related mafic volcanism and the deposition
1995 of banded iron formation. *Journal of Geophysical Research*, 104, 5,461–15,477
- 1996 Jabłońska, J., and Tawfik, D.S. (2021) The evolution of oxygen-utilizing enzymes
1997 suggests early biosphere oxygenation. *Nature Ecology & Evolution*,
1998 <https://doi.org/10.1038/s41559-020-01386-9>

- 1999 Jahn, B.-M., Caby, R., and Monie, P. (2001) The oldest UHP eclogites of the World: age
2000 of UHP metamorphism, nature of protoliths and tectonic implications. *Chemical*
2001 *Geology*, 178, 143–158.
- 2002 Jarrard, R.D. (2003) Subduction fluxes of water, carbon dioxide, chlorine, and potassium.
2003 *Geochemistry Geophysics Geosystems*, 4, 8905.
- 2004 Jenkin, G.R.T., Lusty, P.A.J., McDonald, I., Smith, M.P., Boyce, A.J., and Wilkinson,
2005 J.J. (2015) *Ore Deposits in an Evolving Earth*. Geological Society of London Special
2006 Publication, 393, 1-8.
- 2007 Johannsen, A. (1932–1938) *A Descriptive Petrography of the Igneous Rocks: 4 Volumes*.
2008 University of Chicago Press.
- 2009 Johnson, D., and Watson-Stegner, D. (1987) Evolution model of pedogenesis. *Soil*
2010 *Science*, 143, 349–366.
- 2011 Johnson, T.E., Brown, M., Gardiner, N.J., Kirkland, C.L., and Smithies, R.H. (2017)
2012 Earth's first stable continents did not form by subduction. *Nature*, 543, 239–242.
- 2013 Johnson, S., Graham, H., Des Marais, D.J., and Hazen, R.M. (2020) Detecting life on
2014 Earth and the limits of analogy. In: V. Meadows, Ed., *Planetary Astrobiology*, pp.
2015 121–150. University of Arizona Press.
- 2016 Johnston, C.W., Wyatt, M.A., Li, X., Ibrahim, A., Shuster, J., Southam, G., and
2017 Magarvey, N.A. (2013) Gold biomineralization by a metallophore from a gold-
2018 associated microbe. *Nature Chemical Biology*, 9, 241-243.
- 2019 Jones, A.P., Genge, M., and Carmody, L. (2013) Carbonate melts and carbonatites.
2020 *Reviews in Mineralogy and Geochemistry*, 75, 289-322.

- 2021 Kappler, A., Pasquero, C., Konhauser, K.O., and Newman, D.K. (2005) Deposition of
2022 banded iron formations by photoautotrophic Fe(II)-oxidizing bacteria. *Geology*, 33,
2023 865–868.
- 2024 Kattimani, V.S., Kondaka, S., and Lingamaneni, K.P. (2016) Hydroxyapatite – Past,
2025 present, and future in bone regeneration. *Bone and Tissue Regeneration Insights*,
2026 2016:7, 9–19.
- 2027 Keller, C.B., and Schoene, B. (2012) Statistical geochemistry reveals disruption in
2028 secular lithospheric evolution about 2.5 Gyr ago. *Nature*, 485, 490-493.
- 2029 Kelm, C.N., Nalini, H.A. Jr., and de Lena, J.C. (2015) Manganese oxide biominerals
2030 from freshwater environments in Quadrilatero Ferrifero, Minas Gerais, Brazil.
2031 *Geomicrobiology Journal*, 32, 549-559.
- 2032 Kemp, A.I.S., and Hawkesworth, C.J. (2003) Granitic perspectives on the generation and
2033 secular evolution of the continental crust. In: *Treatise on Geochemistry*. Vol. 3.
2034 Elsevier, pp. 349–410.
- 2035 Kemp, A.I.S., Hawkesworth, C.J., Foster, G.L., Paterson, B.A., Woodhead, J.D., Hergt,
2036 J.M., Gray, C.M., and Whitehouse, M.J. (2007) Magmatic and crustal differentiation
2037 history of granitic rocks from Hf-O isotopes in zircon. *Science*, 315, 980-983.
- 2038 Kennedy, M., Droser, M., Mayer, L.M., Pevear, D., and Mrofka, D. (2006) Late
2039 Precambrian oxygenation; Inception of the clay mineral factory. *Science*, 311, 1446-
2040 1449.
- 2041 Khalidi, M.A. (2013) *Natural Categories and Human Kinds: Classification in the Natural*
2042 *and Social Sciences*. Cambridge University Press.

- 2043 Kierczak, J., and Ettler, V. (2021) Editorial for special issue “Metallurgical slags.”
2044 Minerals, 11, 3 p.
- 2045 Kim, J.D., Yee, N., Nanda, V., and Falkowski, P.G. (2013) Anoxic photochemical
2046 oxidation of siderite generates molecular hydrogen and iron oxides. Proceedings of the
2047 National Academy of Sciences USA, 110, 10073-10077.
- 2048 Kirk, J., Ruiz, J., Chesley, J., Walshe, and England, G. (2002) A major Archean, gold-
2049 and crust-forming event in the Kaapvaal Craton, South Africa. Science, 297, 1856-
2050 1858.
- 2051 Kirschvink, J.L. (1992) Lat Proterozoic low-latitude global glaciation: The snowball
2052 Earth. In: J.W. Schopf, and C. Klein, Eds., The Proterozoic Biosphere: A
2053 Multidisciplinary Study. Cambridge University Press, 51-52.
- 2054 Klein, C. (2005) Some Precambrian banded iron-formations (BIFs) from around the
2055 world: Their age, geologic setting, mineralogy, metamorphism, geochemistry, and
2056 origins. American Mineralogist, 90, 1473-1499.
- 2057 Knauth, L.P. (2005) Temperature and salinity history of the Precambrian ocean:
2058 Implications for the course of microbial evolution. Paleogeography Paleoclimatology
2059 Paleocology, 219, 53-69.
- 2060 Konhauser, K.O., Hamade, T., Raiswell, R., Morris, R.C., Ferris, F.G., Southam, G., and
2061 Canfield, D.E. (2002) Could bacteria have formed the Precambrian banded iron-
2062 formations? Geology, 30, 1079–1082.
- 2063 Korenaga, J. (2008) Plate tectonics, flood basalts, and the evolution of Earth’s oceans.
2064 Terra Nova, 20, 419–439.

- 2065 Korenaga, J. (2018) Crustal evolution and mantle dynamics through Earth history.
2066 Philosophical Transactions of the Royal Society, A376, 20170408.
- 2067 Korenaga, J. (2021) Hadean geodynamics and the nature of early continental crust.
2068 Precambrian Research, in press.
- 2069 Korenaga, J., Planavsky, N.J., and Evans, D.A.D. (2017) Global water cycle and the
2070 coevolution of Earth's interior and surface environment. Philosophical Transactions of
2071 the Royal Society, A375, 20150393.
- 2072 Krivovichev, S.V. (2012) Topological complexity of crystal structures: quantitative
2073 approach. Acta Crystallographica, A68, 393–398.
- 2074 Krivovichev, S.V. (2013) Structural complexity of minerals: information storage and
2075 processing in the mineral world. Mineralogical Magazine, 77, 275–326.
- 2076 Krivovichev, S.V. (2014) Which inorganic structures are the most complex? Angewandte
2077 Chemie International Edition, 53, 654–661.
- 2078 Krivovichev, S.V. (2015) Structural complexity of minerals and mineral parageneses:
2079 information and its evolution in the mineral world. In: R. Danisi and T. Armbruster,
2080 Eds., Highlights in Mineralogical Crystallography. Walter de Gruyter, pp.31–73.
- 2081 Krivovichev, S.V. (2016) Structural complexity and configurational entropy of crystalline
2082 solids. Acta Crystallographica, B72, 274–276.
- 2083 Krivovichev, S.V., Mentré, O., Siidra, O.I., Colmont, M., and Filatov, S.K. (2013)
2084 Anion-centred tetrahedra in inorganic compounds. Chemical Reviews, 113, 6459–
2085 6535.

- 2086 Krivovichev, S.V., Krivovichev, V.G., and Hazen, R.M. (2018) Structural and chemical
2087 complexity of minerals: correlations and time evolution. *European Journal of*
2088 *Mineralogy*, 30, 231-236.
- 2089 Krot, A.N., Scott, E.R.D., and Zolensky, M.E. (1995) Mineralogical and chemical
2090 modification of components in CV3 chondrites: Nebular or asteroidal processing?
2091 *Meteoritics*, 30, 748-775.
- 2092 Krot, A.N., Petaev, M.I., Russell, S.S., Itoh, S., Fagan, T.J., Yurimoto, H., Chizmadia, L.,
2093 Weisberg, M.K., Komatsu, M., Ulyanov, A.A., and Keil, K. (2004) Amoeboid olivine
2094 aggregates and related objects in carbonaceous chondrites: records of nebular and
2095 asteroid processes. *Chemie der Erde Geochemistry*, 64, 185-239.
- 2096 Krot, A.N., Keil, K., Scott, E.R.D., Goodrich, C.A., and Weisberg, M.K. (2014)
2097 Classification of meteorites and their genetic relationships. *Treatise on Geochemistry*,
2098 2nd edition, 1, 2-63.
- 2099 Kruszewski, Ł. (2013) Supergene minerals from the burning coal mining dumps in the
2100 Upper Silesian Coal Basin, South Poland. *International Journal of Coal Geology*, 105,
2101 91-109.
- 2102 Kurokawa, H., Foriel, J., Laneuville, M., Houser, C., and Usui, T. (2018) Subduction and
2103 atmospheric escape of Earth's seawater constrained by hydrogen isotopes. *Earth and*
2104 *Planetary Science Letters*, 497, 149–160.
- 2105 Kusky, T.M. [Ed.] (2004) *Precambrian Ophiolites and Related Rocks*. Elsevier.
- 2106 Kusky, T.M., Li, J.-H., and Tucker, R.D. (2001) The Archean Dongwanzi ophiolite
2107 complex, North China craton: 2.505 billion year old oceanic crust and mantle.
2108 *Science*, 295, 1142-1145.

- 2109 Kusky, T.M., and Zhai, M. (2012) The Neoproterozoic ophiolite in the North China craton:
2110 Early Precambrian plate tectonics and scientific debate. *Journal of Earth Science*, 23,
2111 277-284.
- 2112 Lafuente, B., Downs, R.T., Yang, H., and Stone, N. (2015) The power of databases: the
2113 RRUFF project. In: T. Armbruster and R.M. Danisi, Eds., *Highlights in Mineralogical*
2114 *Crystallography*, pp. 1-30. W. De Gruyter.
- 2115 Lambart, S.L., Baker, M.B., and Stolper, E.M. (2016) The role of pyroxenite in basalt
2116 genesis: Melt-PX, a melting parameterization for mantle pyroxenites between 0.9 and
2117 5 GPa. *Journal of Geophysical Research – Solid Earth*, 121, 5708-5735.
- 2118 Lapham, D.M., Barns, J.H., Downey, W. Jr., and Finkelman, R.B. (1980) Mineralogy
2119 associated with burning Anthracite deposits of Eastern Pennsylvania. Commonwealth
2120 of Pennsylvania, Department of Environmental Resources, Bureau of Topographic and
2121 Geologic Survey, Mineral Resources Report 78, 82 pp.
- 2122 Laznicka, P. (1973) Development of nonferrous metal deposits in geological time.
2123 *Canadian Journal of Earth Science*, 10, 18-25.
- 2124 Leach, D.L., Sangster, D.F., Kelley, K.D., Large, R.R., Garven, G., Allen, C.R., Gutzmer,
2125 J., and Walters, S. (2005) Sediment-hosted lead-zinc deposits: A global perspective.
2126 *Economic Geology*, 100th Anniversary Volume, 561-607.
- 2127 Leach, D.L., Bradley, D.C., Huston, D., Pisarevsky, S.A., Taylor, R.D., and Gardoll, S.J.
2128 (2010) Sediment-hosted lead-zinc deposits in Earth history. *Economic Geology*, 105,
2129 593-625.
- 2130 Le Bas, M.J., and Streckeisen, A.L. (1991) The IUGS systematics of igneous
2131 rocks. *Journal of the Geological Society*, 148, 825–833.

- 2132 Le Bas, M.J., Le Maitre, R.W., Streckeisen, A.L., and Zanettin, B. (1986) A chemical
2133 classification of volcanic rocks based on the total alkali-silica diagram. *Journal of*
2134 *Petrology*, 27, 745-750.
- 2135 Lepot, K., Benzerara, K., Brown, G.E., and Philippot, P. (2008) Microbially influenced
2136 formation of 2,724-million-year-old stromatolites. *Nature Geoscience*, 1, 1-4.
- 2137 Li, Q., and Gadd, G.M. (2017) Biosynthesis of copper carbonate nanoparticles by
2138 ureolytic fungi. *Microbiology and Biotechnology*, 101, 7397–7407.
- 2139 Li, Q., Liu, D., Jia, Z., Csetenyi, L., and Gadd, G.M. (2016) Fungal biomineralization of
2140 manganese as a novel source of electrochemical materials. *Current Biology*, 26, 950-
2141 955.
- 2142 Liang, X., Hillier, S., Pendrowski, H., Gray, N., Ceci, A., and Gadd, G.M. (2015)
2143 Uranium phosphate biomineralization by fungi. *Environmental Microbiology*, 17,
2144 2064–2075.
- 2145 Lichtenberger, H.C., Schobert, T., Bartl, M.H., Waite, H., and Stucky, G.D. (2002) High
2146 abrasion resistance with sparse mineralization: Copper biomineral in worm jaws.
2147 *Science*, 298, 389-392.
- 2148 Lins, U., Keim, C.N., Evans, F.F., Farina, M., and Buseck, P.R. (2007) Magnetite (Fe₃O₄)
2149 and greigite (Fe₃S₄) crystals in magnetotactic multicellular organisms.
2150 *Geomicrobiology Journal*, 24, 43–50.
- 2151 Liu, C., Runyon, S.E., Knoll, A.H., and Hazen, R.M. (2019) The same and not the same:
2152 Ore geology, mineralogy and geochemistry of Rodinia assembly versus other
2153 supercontinents. *Earth Science Reviews*, 196, 102860 (33 p.).

- 2154 London, D. (2008) Pegmatites. Mineralogical Association of Canada Special Publication,
2155 10, 347 p.
- 2156 Lowell, R.P., and Rona, P.A. (2002) Seafloor hydrothermal systems driven by the
2157 serpentinization of peridotite. *Geophysical Research Letters*, 29, 1-5.
- 2158 Lowell, R.P., Seewald, J.S., Metaxas, A., and Perfit, M.R. [Eds] (2008) Magma to
2159 Microbe Modeling Hydrothermal Processes at Oceanic Spreading Centers. American
2160 Geophysical Union Monograph Series, 178.
- 2161 Lowenstam, H.A., and Weiner, S. (1989) On Biomineralization. Oxford University Press.
- 2162 Lu, A., Li, Y., Liu, F., Liu, Y., Ye, H., Zhuang, Z., Li, Y., Ding, H., and Wang, C. (2021)
2163 The photogeochemical cycle of Mn oxides on the Earth's surface. *Mineralogical*
2164 *Magazine*, 85, 22-38.
- 2165 Luth, R.W. (2003) Mantle volatiles -- distribution and consequences. In: R.W. Carlson
2166 [Ed.], *The Mantle and Core*, Elsevier-Pergamon, pp. 319-361.
- 2167 Lyons, T.W., Reinhard, C.T., and Planavsky, N.J. (2014) The rise of oxygen in Earth's
2168 early ocean and atmosphere. *Nature*, 506, 307-314.
- 2169 Lysyuk, G.N. (2008) Biomineral nanostructures of manganese oxides in oceanic
2170 ferromanganese nodules. *Geology of Ore Deposits*, 50, 647-649.
- 2171 MacPherson, G.J. (2014) Calcium-aluminum-rich inclusions in chondritic meteorites. In
2172 *Treatise on Geochemistry*, Vol. 1: Meteorites, Comets, and Planets, Second Edition.
2173 A.M. Davis, H.D.Holland, and K.K.Turekian, Eds., pp.139-179. Elsevier-Pergamon.
- 2174 Magnus, P.D. (2012) *Scientific Enquiry and Natural Kinds: From Mallards to Planets*.
2175 Palgrave MacMillan.

- 2176 Maier, W.D., and Groves, D.I. (2011) Temporal and spatial controls on the formation of
2177 magmatic PGE and Ni-Cu deposits. *Mineralum Deposita*, 46, 841-857.
- 2178 Manning, C.E., and Frezzotti, M.L. (2020) Subduction-zone fluids. *Elements*, 16, 395-
2179 400.
- 2180 Marks, M.A.W., and Markl, G. (2017) A global review on agpaitic rocks. *Earth Science*
2181 *Reviews*, 173, 229-258.
- 2182 Martshall, K.C. (1979) Biogeochemistry of manganese minerals. *Studies in*
2183 *Environmental Science*, 3, 253-292.
- 2184 Marty, B., Avice, G., Bekaert, D.V., and Broadley, M.W. (2018) Salinity of the Archean
2185 oceans from analysis of fluid inclusions in quartz. *Comptes Rendus Geoscience*, 350,
2186 154-163.
- 2187 Maynard-Casely, H.E., Cable, M.L., Malaska, M.J., Vu, T.H., Choukroun, M., and
2188 Hodyss, R. (2018) Prospects for mineralogy on Titan. *American Mineralogist*, 103,
2189 343-349.
- 2190 McSween, H.Y. Jr., Sears, D.W.G., and Dodd, R.T. (1988) Thermal metamorphism. In:
2191 J.F. Kerridge and M.S. Matthews, Eds., *Meteorites and the Early Solar System*, pp.
2192 102-113. University of Arizona Press.
- 2193 Menez, B., Pisapia, C., Andreani, M., Jamme, F., Vanbellingen, Q.P., Brunelle, A.,
2194 Richard, L., Dumas, P., and Refregiers, M. (2018) Abiotic synthesis of amino acids in
2195 the recesses of the oceanic lithosphere. *Nature*, 564, 59-63.
- 2196 Merlino, S., and Sartori, F. (1970) Santite, a New Mineral Phase from Larderello,
2197 Tuscany. *Contributions to Mineralogy and Petrology*, 27, 159-165.

- 2198 Meyer, C. (1988) Ore deposits as guides to geologic history of the Earth. Annual Review
2199 of Earth and Planetary Sciences, 16, 147-171.
- 2200 Mikhailova, J.A., Ivanyuk, G.Y., Kalashnikov, A.O., Pakhomovsky, A.V.B., Bazai, A.V.,
2201 and Yakovenchuk, V.N. (2019) Petrogenesis of the eudialyte complex of the Lovozero
2202 Alkaline Massif (Kola Peninsula, Russia). Minerals, 9, 581 (31 p.).
- 2203 Mills, S.J., Hatert, F., Nickel, E.H., and Ferrais, G. (2009) The standardization of mineral
2204 group hierarchies: Application to recent nomenclature proposals. European Journal of
2205 Mineralogy, 21, 1073-1080.
- 2206 Milton, C., Dworkin, E.J., Estep-Barnes, P.A., Finkelman, R.B., Pabst, A., and Palmer, S.
2207 (1978) Abelsonite, nickel porphyrin, a new mineral from the Green River Formation,
2208 Utah. American Mineralogist, 63, 930-937.
- 2209 Mitchell, R.H. (1986) Kimberlites: Mineralogy, Geochemistry, and Petrology. Springer.
- 2210 Mitchell, R.H., Giuliani, A., and O'Brien, H. (2019) What is a kimberlite? Petrology and
2211 mineralogy of hypabyssal kimberlites. Elements, 15, 381-386.
- 2212 Mittlefehldt, D.W. (2014) Achondrites. Treatise on Geochemistry, 2nd edition, 1, 235-
2213 266.
- 2214 Mittlefehldt, D.W., McCoy, T.J., Goodrich, C.A., and Kracher, A. (1998) Non-chondritic
2215 meteorites from asteroidal bodies. Reviews in Mineralogy, 36, 4.1-4.195.
- 2216 Mojzsis, S.J., Harrison, T.M., and Pidgeon, R.T. (2001) Oxygen-isotope evidence 1831
2217 from ancient zircons for liquid water at the Earth's surface 4,300 Myr ago. Nature,
2218 409, 178-181.
- 2219 Moore, W.B., and Webb, A.A.G. (2013) Heat-pipe Earth. Nature, 501, 501-505.

- 2220 Moores, E.M. (2002) Pre-1 Ga (pre-Rodinian) ophiolites: their tectonic and
2221 environmental implications. *GSA Bulletin*, 114, 80–95.
- 2222 Morrison, S.M., and Hazen, R.M. (2020) An evolutionary system of mineralogy, Part II:
2223 Interstellar and solar nebula primary condensation mineralogy (> 4.565 Ga). *American*
2224 *Mineralogist*, 105, 1508-1535.
- 2225 Morrison, S.M., and Hazen, R.M. (2021) An evolutionary system of mineralogy, Part IV:
2226 Planetary differentiation and impact mineralization (4.566 to 4.560 Ga). *American*
2227 *Mineralogist*, in press.
- 2228 Morrison, S.M., Runyon, S.E., and Hazen, R.M. (2018) The paleomineralogy of the
2229 Hadean Eon revisited. *Life*, 8, 64. DOI: 10.3390/life8040064
- 2230 Morrison, S.M., Buongiorno, J., Downs, R.T., Eleish, A., Fox, P., Giovannelli, D.,
2231 Golden, J.J., Hummer, D.R., Hystad, G., Kellogg, L.H., Kreylos, O., Krivovichev,
2232 S.V., Liu, C., Prabhu, A., Ralph, J., Runyon, S.E., Zahirovic, S., and Hazen, R.M.
2233 (2020) Exploring carbon mineral systems: Recent advances in C mineral evolution,
2234 mineral ecology, and network analysis. *Frontiers in Earth Sciences*. DOI:
2235 10.3389/feart.2020.00208
- 2236 Moyen, J.-F., and van Hunen, J. (2012) Short-term episodicity of Archaean plate
2237 tectonics. *Geology*, 40, 451–454.
- 2238 Mukherjee, I., Large, R.R., Corkrey, R., and Danyushevsky, L.V. (2018) The boring
2239 billion, a slingshot for complex life on Earth. *Scientific Reports*, 8, 4432.
- 2240 Mungall, J.E., and Naldrett, A.J. (2008) Ore deposits of the platinum-group elements.
2241 *Elements*, 4, 253-258.

- 2242 Mustoe, G.E. (2018) Mineralogy of non-silicified fossil wood. *Geosciences*, 8, Article 85,
2243 32 p.
- 2244 Naldrett, A.J., Cameron, G., von Gruenewaldt, G., and Sharpe, M.R. (1987) The
2245 formation of stratiform PGE deposits in layered intrusions. In: I. Parson, Ed., *Origins*
2246 *of Igneous Layering*. Springer, pp. 313-397.
- 2247 Nance, R.D., Murphy, J.B., and Santosh, M. (2014) The supercontinent cycle: A
2248 retrospective essay. *Gondwana Research*, 25, 4–29.
- 2249 Nash, J.T., Granger, H.C., and Adams, S.S. (1981) Geology and concepts of genesis of
2250 important types of uranium deposits. *Economic Geology*, 75th Anniversary Volume,
2251 63-116.
- 2252 Nazarchuk, E.V., Siidra, O.I., Agakhanov, A.A., Lukina, E.A., Avdontseva, E.Y., and
2253 Karpov, G.A. (2018) Itelmenite, $\text{Na}_2\text{CuMg}_2(\text{SO}_4)_4$, a new anhydrous sulfate mineral
2254 from the Tolbachik volcano. *Mineralogical Magazine*, 82, 1233-1241.
- 2255 Nickel, E.H., and Grice, J.D. (1998) The IMA Commission on New Minerals and
2256 Mineral Names: Procedures and guidelines on mineral nomenclature. *Canadian*
2257 *Mineralogist*, 36, 17-18.
- 2258 Nishimoto, S., and Yoshida, H. (2010) Hydrothermal alteration of deep-fractured granite:
2259 Effects of dissolution and precipitation. *Lithos*, 115, 153-162.
- 2260 Nittler, L.R., and Ciesla, F. (2016) Astrophysics with extraterrestrial materials. *Annual*
2261 *Reviews of Astronomy and Astrophysics*, 54, 53-93.
- 2262 Nutman, A.P., and Friend, C.R.L. (2007) Comment on “A vestige of Earth’s oldest
2263 ophiolite”. *Science*, 318, 746.

- 2264 O'Driscoll, B., and VanTongeren, J.A. (2017) Layered intrusions: From petrological
2265 paradigms to precious metal repositories. *Elements*, 13, 383-389.
- 2266 O'Neil, J., Carlson, R.W., Francis, D., and Stevenson, R.K. (2008) Neodymium-142
2267 evidence for Hadean mafic crust. *Science*, 321, 1828-1831.
- 2268 O'Neill, C., Lenardic, A., Moresi, L., Torsvik, T.H., and Lee, C.-T. (2007) Episodic
2269 Precambrian subduction. *Earth and Planetary Science Letters*, 262, 552–562.
- 2270 O'Reilly, S.Y., and Griffin, W.L. (2012) Mantle metasomatism. In: D.E. Harlov and H.
2271 Austrheim, Eds., *Metasomatism and the Chemical Transformation of Rock*, pp. 471-
2272 533. Springer.
- 2273 Palandri, J.L., and Reed, M.H. (2004) Geochemical models of metasomatism in
2274 ultramafic systems: Serpentinization, rodingitization, and sea floor carbonate chimney
2275 precipitation. *Geochimica et Cosmochimica Acta*, 68, 1115- 1133.
- 2276 Palin, R.M., and White, R.W. (2016) Emergence of blueschists on Earth linked to secular
2277 changes in oceanic crust composition. *Nature Geoscience*, 9, 60–64.
- 2278 Papineau, D. (2010) Mineral environments on the earliest Earth. *Elements*, 6, 25-30.
- 2279 Paris, F., Bonnard, P., Ranger, J., and Lapeyrie, F. (1995) In vitro weathering of
2280 phlogopite by ectomycorrhizal fungi: I. Effect of K^+ and Mg^{2+} deficiency on
2281 phyllosilicate evolution. *Plant and Soil*, 177, 191-201.
- 2282 Paris, F., Bottom, B., and Lapeyrie, F. (1996) In vitro weathering of phlogopite by
2283 ectomycorrhizal fungi: II. Effect of K^+ and Mg^{2+} deficiency and N sources on
2284 accumulation of oxalate and H^- . *Plant and Soil*, 179, 141-150.

- 2285 Pasek, M.A., and Block, K. (2009) Lightning-induced reduction of phosphorus oxidation
2286 state. *Nature Geoscience*, 2, 553-556.
- 2287 Pasek, M.A., Block, K., and Pasek, V. (2012) Fulgurite morphology: A classification
2288 scheme and clues to formation. *Contributions to Mineralogy and Petrology*, 164, 477-
2289 492.
- 2290 Passchier, C.W., and Trouw, R.A.J. (2005) *Microtectonics*, Second Edition. Springer.
- 2291 Patchett, J.P., Kuovo, O., Hedge, C.E., and Tatsumoto, M. (1982) Evolution of
2292 continental crust and mantle heterogeneity: Evidence from Hf isotopes. *Contributions*
2293 *to Mineralogy and Petrology*, 78, 279-297.
- 2294 Pekov, I.V., Kovrugin, V.M., Siidra, O.I., Chukanov, N.V., Belakovskiy, D.I.,
2295 Koshlyakova, N.N., Yapaskurt, V.O., Turchkova, A.G., and Möhn, G. (2019)
2296 Antofagastaite, $\text{Na}_2\text{Ca}(\text{SO}_4)_2 \cdot 1.5\text{H}_2\text{O}$, a new mineral related to syngenite.
2297 *Mineralogical Magazine*, 83, 781-790
- 2298 Perry, R.S., Mcloughlin, N., Lynne, B.Y., Sephton, M.A., Oliver, J.D., Perry, C.C.,
2299 Campbell, K., Engel, M.H., Farmer, J.D., Brasier, M.D., and Staley, J.T. (2007)
2300 Defining biominerals and organominerals: Direct and indirect indicators of life.
2301 *ScienceDirect*, 201, 157-179.
- 2302 Peters, T.A., Koestler, R.J., Peters, J.J., and Grube, C.H. (1983) Minerals of the
2303 Buckwheat dolomite, Franklin, New Jersey. *Mineralogical Record*, 14, 183-194.
- 2304 Philpotts, A.R., and Ague, J.J. (2009) *Principles of Igneous and Metamorphic Petrology*,
2305 Second Edition. Cambridge University Press.
- 2306 Ping, H., Xie, H., Xiang, M., Su, B.-L., Wang, Y., Zhang, J., Zhang, F., and Fu, Z. (2016)
2307 Confined-space synthesis of nanostructured anatase, directed by genetically

- 2308 engineered living organisms for lithium-ion batteries. *Chemical Science*, 7, 6330-
2309 6336.
- 2310 Piper, J.D.A. (2013) A planetary perspective on Earth evolution: Lid tectonics before
2311 plate tectonics. *Tectonophysics*, 589, 44–56.
- 2312 Pirajno, F. (2009) *Hydrothermal Processes and Mineral Systems*. Springer.
- 2313 Plazo-Toledo, M. (2019) The mineral industry of Iceland. 2016 Minerals Yearbook, pp.
2314 21.1-21.2. United States Geological Survey.
- 2315 Pósfai, M., Buseck, P.R., Bazylinski, D.A., and Frankel, R.B. (1998) Reaction sequence
2316 of iron sulfide minerals in bacteria and their use as biomarkers. *Science*, 280, 880-883.
- 2317 Pósfai, M., Lefèvre, C.T., Trubitsyn, D., Bazylinski, D.A., and Frankel, R.B. (2013)
2318 Phylogenetic significance of composition and crystal morphology of magnetosome
2319 minerals. *Frontiers in Microbiology*, 4, Article 344.
- 2320 Post, J.E. (1999) Manganese oxide minerals: Crystal structures and economic and
2321 environmental significance. *Proceedings of the National Academy of Sciences USA*,
2322 96, 3447-3454.
- 2323 Prabhu, A., Morrison, S., Eleish, A., Zhong, H., Huang, F., Golden, J., Perry, S.,
2324 Hummer, D., Runyon, S., Fontaine, K., Krivovichev, S., Downs, R., Hazen, R., and
2325 Fox, P. (2021) Global Earth mineral inventory: A data legacy. *Geoscience Data*
2326 *Journal*, in press.
- 2327 Prokoph, A., Ernst, R.E., Buchan, K.L. (2004) Time-series analysis of Large Igneous
2328 Provinces: 3500 Ma to present. *Journal of Geology*, 112, 1–22.

- 2329 Reimink, J.R., Pearson, D.G., Shirey, S.B., Carlson, R.W., and Ketchum, J.W.F. (2019)
2330 Onset of new, progressive crustal growth in the central Slave craton at 3.5 Ga.
2331 Geochemical Perspectives Letters, 10, 7-12.
- 2332 Reith, F., Rogers, S.L., McPhail, D.C., and Webb, D. (2006) Biomineralization of gold:
2333 Biofilms on bacterioform gold. Science, 313, 233-236.
- 2334 Reith, F., Etschmann, B., Grosse, C., Moors, H., Benotmane, M.A., Monsieurs, P., Grass,
2335 G., Doonan, C., Vogt, S., Lai, B., Martinez-Craido, G., George, G.N., Nies, D.H.,
2336 Mergeay, M., Pring, A., Southam, G., and Brugger, J. (2009) Mechanisms of gold
2337 biomineralization in the bacterium *Cupriavidus metallidurans*. Proceedings of the
2338 National Academy of Sciences USA, 106, 17757-17762.
- 2339 Remy, W., Taylor, T.N. Hass, H, and Kerp, H. (1994) Four hundred-million-year old
2340 vesicular arbuscular mycorrhizae. Proceedings of the National Academy of Sciences,
2341 91, 11841–11843.
- 2342 Retallack, G.J. (2001) Soils of the Past: An Introduction to Paleopedology. Blackwell
2343 Science.
- 2344 Rodgers, A.L. (1997) Effect of mineral water containing calcium and magnesium on
2345 calcium oxalate urolithiasis risk factors. Urology International, 58, 93-99.
- 2346 Rollinson, H. (2007a) When did plate tectonics begin? Geology Today, 23, 186-189.
- 2347 Rollinson, H. (2007b) Early Earth Systems: A Geochemical Approach. Blackwell
2348 Publishing.
- 2349 Rosas, J.C., and Korenaga, J. (2018) Rapid crustal growth and efficient crustal recycling
2350 in the early Earth: Implications for Hadean and Archean geodynamics. Earth and
2351 Planetary Science Letters, 494, 42–49.

- 2352 Rosas, J.C., and Korenaga, J. (2021) Archean seafloor shallowed with age due to
2353 radiogenic heating in the mantle. *Nature Geoscience*, 14, 51–56.
- 2354 Rubin, A.E., and Ma, C. (2021) *Meteorite Mineralogy*. Cambridge University Press.
- 2355 Russell, S.A., Connolly, H.C. Jr., and Krot, A.N. [Eds]. (2018) *Chondrules: Records of*
2356 *Protoplanetary Disk Processes*. Cambridge University Press.
- 2357 Rye, R., and Holland, H.D. (1998) Paleosols and the evolution of atmospheric oxygen: A
2358 critical review. *American Journal of Science*, 298, 621-672.
- 2359 Sangster, D.F. (1972) Precambrian volcanogenic massive sulfide deposits in Canada: A
2360 review. *Geological Survey of Canada Paper*, 72-22, pp. 1-43.
- 2361 Sanyal, S.K., and Shuster, J. (2021) Gold particle geomicrobiology: Using viable bacteria
2362 as a model for understanding microbe-mineral interactions. *Mineralogical Magazine*,
2363 85, 117-124.
- 2364 Savage, D., Cave, M.R., Milodowski, A.E., and George, I. (1987) Hydrothermal
2365 alteration of granite by meteoric fluid: an example from the Carnmenellis Granite,
2366 United Kingdom. *Contributions to Mineralogy and Petrology*, 96, 391-405.
- 2367 Saxby, J.D. (2000) Minerals in coal. In: M. Gilkson, and M.Mastalerez, Eds., *Organic*
2368 *Matter and Mineralisation: Thermal Alteration, Hydrocarbon Generation and Role in*
2369 *Metallogenesis*. Springer.
- 2370 Schertl, H.-P., Mills, S.J., and Maresch, W.V. (2018) *A Compendium of IMA-Approved*
2371 *Mineral Nomenclature*. International Mineralogical Association.
- 2372 Schulz, H.N., and Schulz, H.D. (2005) Large sulfur bacteria and the formation of
2373 phosphorite. *Science*, 307, 416-419.

- 2374 Schwartzman, D.W., and Volk, T. (1989) Biotic enhancement of weathering and the
2375 habitability of Earth. *Nature*, 340, 457-460.
- 2376 Schwartzenbach, E.M., and Steele-MacInnis, M. (2020) Fluids in submarine mid-ocean
2377 ridge hydrothermal settings. *Elements*, 16, 389-394.
- 2378 Schweinfurth, S.P. (2016) Coal – A Complex Natural Resource. United States Geological
2379 Survey Circular, 1143, 40 p.
- 2380 Sherman, G.D., Walker, J.L., and Ikawa, H. (1968) Some of the Mineral Resources of the
2381 Hawaiian Islands. Hawaii Agricultural Experiment Station Bulletin No. 138,
2382 University of Hawaii, 35 p.
- 2383 Shirey, S.B., and Richardson, S.H. (2011) Start of the Wilson Cycle at 3 Ga shown by
2384 diamonds from subcontinental mantle. *Science*, 333, 434-436.
- 2385 Shirey, S.B., Kamber, B.S., Whitehouse, M.J., Mueller, P.A., and Basu, A.R. (2008) A
2386 review of the isotopic and trace element evidence for mantle and crustal processes in
2387 the Hadean and Archean: Implications for the onset of plate tectonic subduction. In:
2388 Condie, K., and Pease, V., Eds., *When Did Plate Tectonics Begin on Earth?*
2389 Geological Society of America Special Paper, 3440, 1-29.
- 2390 Shrenk, M.O., Brazelton, W.J., and Lang, S.Q. (2013) Serpentinization, carbon, and deep
2391 life. *Reviews in Mineralogy & Geochemistry*, 75, 575-606.
- 2392 Smith, G.F.H., and Prior, G.T. (1899) On some lead minerals from Laurium, namely,
2393 laurionite, phosgenite, fiedlerite, and (new species) paralaurionite. *Mineralogical*
2394 *Magazine*, 12, 102-110.
- 2395 Sokol, E.V., Novikov, I.S., Zateeva, S.N., Sharygin, V.V., and Vapnik, Y. (2008)
2396 Pyrometamorphic rocks of the spurrite-merwinite facies as indicators of hydrocarbon

- 2397 discharge zones (the Hatrurim formation, Israel). *Doklady Earth Sciences*, 420, 608-
2398 614.
- 2399 Sokol, E.V., Kokh, S.N., Sharygin, V.V., Danilovsky, V.A., Seryotkin, Y.V., Liferovich,
2400 R., Deviatiiarova, A.S., Nigmatulina, E.N., and Karmanov, N.S. (2019) Mineralogical
2401 diversity of Ca₂SiO₄-bearing combustion metamorphic rocks in the Hatrurim Basin:
2402 Implications for storage and partitioning of elements in oil shale clinkering. *Minerals*,
2403 9, Article 465, 61 p.
- 2404 Southam, G., and Saunders, J.A. (2005) The geomicrobiology of ore deposits. *Economic*
2405 *Geology*, 100, 1067-1084.
- 2406 Spry, P.G., Plimer, I.R., and Teale, G.S. (2008) Did the giant Broken Hill (Australia) Zn-
2407 Pb-Ag deposit melt? *Ore Geology Reviews*, 34, 223-241.
- 2408 Steele-MacInnis, M., and Manning, C.E. (2020) Hydrothermal properties of geologic
2409 fluids. *Elements*, 16, 375-380.
- 2410 Stern, R.J. (2005) Evidence from ophiolites, blueschists, and ultrahigh-pressure
2411 metamorphic terranes that the modern episode of subduction tectonics began in
2412 Neoproterozoic time. *Geology*, 33, 557-560.
- 2413 Stern, R.J. (2018) The evolution of plate tectonics. *Philosophical Transactions of the*
2414 *Royal Society*, A376, 20170406.
- 2415 Stracher, G.B., Prakash, A., and Sokol, E.V. [Editors] (2015) *Coal and Peat Fires*.
2416 Volume 3. Case Studies – Coal Fires. Elsevier Science, 786 p.
- 2417 Streckeisen, A.L. (1976) To each plutonic rock its proper name. *Earth Science Reviews*,
2418 12, 1-33.

- 2419 Streckeisen, A.L. (1979) Classification and nomenclature of volcanic rocks,
2420 lamprophyres, carbonatites, and melilitic rocks: Recommendations and suggestions of
2421 the IUGS Subcommittee on the Systematics of Igneous Rocks. *Geology*, 7, 331-335.
- 2422 Sueoka, Y., and Sakakibara, M. (2013) Primary phases and natural weathering of
2423 smelting slag at an abandoned mine site in southwest Japan. *Minerals*, 3, 412-426.
- 2424 Sugitani, K., Mimura, K., Suzuki, K., Nagamine, K., and Sugisaki, R. (2003) Stratigraphy
2425 and sedimentary petrology of an Archean volcanic sedimentary succession at Mt.
2426 Goldsworthy in the Pilbara Block, Western Australia: implications of evaporite
2427 (nahcolite) and barite deposition. *Precambrian Research*, 120, 55-79.
- 2428 Suzuki, Y., and Banfield, J.F. (1999) Geomicrobiology of uranium. *Reviews in*
2429 *Mineralogy*, 38, 393-432.
- 2430 Sverjensky, D.A., and Lee, N. (2010) The Great Oxidation Event and mineral
2431 diversification. *Elements*, 6, 31-36.
- 2432 Tang, M., Chen, K., and Rudnick, R.L. (2016) Archean upper crust transition from mafic
2433 to felsic marks the onset of plate tectonics. *Science*, 351, 372–375.
- 2434 Tang, M., Chu, X., Hao, J., and Shen, B. (2021) Orogenic quiescence in Earth's middle
2435 age. *Science*, 371, 728-731.
- 2436 Taylor, S.R., and McLennan, S.M. (1995) The geochemical evolution of the continental
2437 crust. *Reviews in Geophysics*, 33, 241–265.
- 2438 Thiemens, M.M., Sprung, P., Fonseca, R.O.C., Leitzke, F.P., and Munker, C. (2019)
2439 Early Moon formation inferred from hafnium-tungsten systematics. *Nature*
2440 *Geosciences*, 12, 696–700.

- 2441 Titley, S.R. (1993) Relationship of stratabound ores with tectonic cycles of the
2442 Phanerozoic and Proterozoic. *Precambrian Research*, 61, 295-322.
- 2443 Tkachev, A.V. (2011) Evolution of metallogeny and granite pegmatites associated with
2444 orogens throughout geological time. In: Saal, A.N., Bettencourt, J.S., De Campos,
2445 C.P., and Ferreira, V.P., Eds., *Granite-Related Ore Deposits*. Geological Society of
2446 London, Special Publications, 350, 7-23.
- 2447 Tomioka, N., and Miyahara, M. (2017) High-pressure minerals in shocked meteorites:
2448 *Meteoritics & Planetary Science*, 52, 2017-2039.
- 2449 Trouw, R.A.J., Passchier, C.W., and Wiersma, D.J. (2009) *Atlas of Mylonites and*
2450 *Related Microstructures*. Springer.
- 2451 Tschauner, O. (2019) High-pressure minerals. *American Mineralogist*, 104, 1701-1731.
- 2452 Turner, S., Wilde, S., Wörner, G., Schaefer, B., and Lai, Y.-J. (2020) An andesitic source
2453 for Jack Hills zircon supports onset of plate tectonics in the Hadean. *Nature*
2454 *Communications*, 11, 1241
- 2455 Uebe, R., and Schüler, D. Magnetosome biogenesis in magnetotactic bacteria. *Nature*
2456 *Reviews Microbiology*, 14, 621-637.
- 2457 Ueshima, M. and Tazaki, K. (1998) Bacterial bio-weathering of K-feldspar and biotite in
2458 granite. *Clay Science Japan*, 38, 68-92.
- 2459 van Hunen, J., and Moya, J.-F. (2012) Archean subduction: fact or fiction? *Annual*
2460 *Review of Earth and Planetary Sciences*, 40, 195–219.
- 2461 Van Kranendonk, M.J., Webb, G.E., and Kamber, B.S. (2003) Geological and trace
2462 element evidence for a marine sedimentary environment of deposition and biogenicity

- 2463 of 3.45 Ga stromatolitic carbonates in the Pilbara Craton, and support for a reducing
2464 Archean ocean. *Geobiology*, 1, 91-108.
- 2465 Van Kranendonk, M.J., Collins, W.J., Hickman, A., and Pawley, M.J. (2004) Critical
2466 tests of vertical vs. horizontal tectonic models for the Archaean East Pilbara Granite-
2467 Greenstone Terrane, Pilbara Craton, Western Australia. *Precambrian Research*, 131,
2468 173–211.
- 2469 Van Kranendonk, M.J., Smithies, R.H., Hickman, A.H., and Champion, D. (2007a)
2470 Review: secular tectonic evolution of Archean continental crust: interplay between
2471 horizontal and vertical processes in the formation of the Pilbara Craton, Australia.
2472 *Terra Nova*, 19, 1–38.
- 2473 Van Kranendonk, M.J., Smithies, R.H., and Bennett, V.C. [Editors] (2007b) Earth's
2474 Oldest Rocks. *Developments in Precambrian Geology*, 15. Elsevier.
- 2475 Van Tassel, R. (1945) Une efflorescence d'acétatochlorure de calcium sur des roches
2476 calcaires dans des collections. *Bulletin du Musée Royal d'Histoire Naturelle de*
2477 *Belgique*, 21, 1-11.
- 2478 Vergasova, L.P., and Filatov, S.K. (2016) A study of volcanogenic exhalation
2479 mineralization. *Journal of Volcanology and Seismology*, 10, 71–85.
- 2480 Vernon, R.H. (2008) *Principles of Metamorphic Petrology*. Cambridge University Press.
- 2481 Voosen, P. (2021) Ancient Earth was a water world. *Science*, 371, 1088-1089.
- 2482 Weiner, S., and Wagner, H.D. (1998) The material bone: structure-mechanical function
2483 relations. *Annual Review of Materials Science*, 28, 271–298.

- 2484 Walenta, K., and Dunn, P.J. (1984) Arsenogoyazit, ein neues mineral der
2485 Crandallitgruppe aus dem Schwarzwald. Schweizerische Mineralogische und
2486 Petrographische Mitteilungen, 64, 11-19.
- 2487 Wegorzewski, A.V., and Kuhn, T. (2014) The influence of suboxic diagenesis on the
2488 formation of manganese nodules in the Clarion Clipperton nodule belt of the Pacific
2489 Ocean. Marine Geology, 357, 123–138.
- 2490 Wenk, H.-R., and Bulakh, A. (2016) Minerals: Their Constitution and Origin. Second
2491 Edition. Cambridge University Press.
- 2492 Whittet, D.C.B. (2003) Dust in the Galactic Environment. Institute of Physics Publishing.
- 2493 Wilde, S.A., Valley, J.W., Peck, W.H., and Graham, C.M. (2001) Evidence from detrital
2494 zircons for the existence of continental crust and oceans on Earth 4.4 Gyr ago. Nature,
2495 409, 175-178.
- 2496 Wilson, M.J. (2013) Rock-Forming Minerals. Volume 3C, Second Edition. Sheet
2497 Silicates: Clay Minerals. Wiley.
- 2498 Wilson, M.J., and Bain, D.C. (1986) Spheniscidite, a new phosphate mineral from
2499 Elephant Island, British Antarctic Territory. Mineralogical Magazine, 50, 291-293.
- 2500 Woolley, A.R., and Kjarsgaard, B.A. (2008) Carbonatite occurrences of the world: map
2501 and database. Geological Survey of Canada Open File 5796,
- 2502 Wufuer, R., Wei, Y., Lin, Q., Wang, H., Song, W., Liu, W., Zhang, D., Pan, X., and
2503 Gadd, G.M. (2017) Uranium bioreduction and biomineralization. Advances in Applied
2504 Microbiology, 101, 137-168.

- 2505 Yang, H., Sun, H.J., and Downs, R.T. (2011) Hazenite, $\text{KNaMg}_2(\text{PO}_4)_2 \cdot 14\text{H}_2\text{O}$, a new
2506 biologically related phosphate mineral, from Mono Lake, California, U.S.A. American
2507 Mineralogist, 96, 675-681.
- 2508 Yoder, H.S. Jr. (2002) Geology: Significant component of new multidisciplinary
2509 sciences. Proceedings of the American Philosophical Society, 146, 37-55.
- 2510 Zahnle, K.J. (2006) Earth's earliest atmosphere. Elements, 2, 217-222.
- 2511 Zahnle, K.J., Arndt, N., Cockell, C., Halliday, A., Nisbet, E., Selsis, F., and Sleep, N.H.
2512 (2007) Emergence of a habitable planet. Space Science Reviews, 129, 35-78.
- 2513 Zaikowski, L., and Friedrich, J.M. [Eds] (2007) Chemical Evolution I: Chemical Change
2514 across Space and Time. American Chemical Society Symposium, 981.
- 2515 Zeng, Z., Ali, S.H., Tian, J., and Li, J. (2020) Mapping anthropogenic mineral generation
2516 in China and its implications for a circular economy. Nature Communications, 11,
2517 Article number 1554.
- 2518 Zerfaß, C., Christie-Oleza, J.A., and Sover, O.S. (2019) Manganese oxide
2519 biomineralization provides protection against nitrate toxicity in a cell-density-
2520 dependent manner. Applied Environmental Microbiology, 85, e02129-18.
- 2521 Zhai, M., Zhao, G., and Zhang, Q. (2002) Is the Dongwanzi Complex an Archean
2522 ophiolite? Science, 295, 923.
- 2523 Zheng, Y.-F., and Chen, R.-X. (2017) Regional metamorphism at extreme conditions:
2524 Implications for orogeny at convergent plate margins. Journal of Asian Earth Sciences,
2525 145, 46-73.

- 2526 Zientek, M.L. (2012) Magmatic ore deposits in layered intrusions – Descriptive model
2527 for reef-type PGE and contact-type Cu-Ni-PGE deposits. United States Geological
2528 Survey, Open-File Report, 2012-1010.
- 2529 Zinner, E.K. (2014) Presolar grains. In Treatise on Geochemistry, Vol. 1: Meteorites,
2530 Comets, and Planets, Second Edition. A.M. Davis, H.D. Holland, and K.K. Turekian,
2531 Eds., pp.17-39. Oxford: Elsevier-Pergamon.

Table 1. Chronological list of 57 paragenetic modes of minerals, with numbers of associated mineral species

Paragenetic Mode*	Age (Ga)	#Species**	#Unique***	Ref.****
<i>Pre-terrestrial “Ur-minerals”</i>	<u>> 4.57</u>	<u>30</u>	<u>8</u>	
1. Stellar atmosphere condensates		22	1	1-4
2. Interstellar condensates*****		8	7	5-7
<i>Stage 1: Primary nebular phases</i>	<u>4.567—4.561</u>	<u>86</u>	<u>14</u>	
3. Solar nebular condensates (CAIs, AOAs, URIs)	> 4.565	48	14	7-12
4. Primary chondrule phases	4.566—4.561	47	0	11-15
<i>Stage 2: Planetesimal differentiation & alteration</i>	<u>4.566—4.550</u>	<u>261</u>	<u>65</u>	
5. Primary asteroid phases	4.566—4.560	94	21	11,13,16-18
6. Secondary asteroid phases	4.565—4.550	205	44	11,12,16,17,19-21
<i>Stage 3a: Earth’s earliest Hadean crust</i>	<u>> 4.50</u>	<u>400</u>	<u>61</u>	22-26
7. Ultramafic igneous rocks		123	10	22,23,27
8. Mafic igneous rocks		93	6	22,23,28-33
9. Lava/xenolith minerals (hornfels, sanidinite facies)		127	8	22,23,34
10. Basalt-hosted zeolite minerals		107	30	35
11. Volcanic fumarole minerals; reduced phases (see also [#45])		36	7	34,36
<i>Stage 3b: Earth’s earliest hydrosphere</i>	<u>≥ 4.45</u>	<u>350</u>	<u>64</u>	37,38
12. Hadean hydrothermal subsurface sulfide deposits (see also [#33])		129	48	39-43
13. Hadean serpentinization		67	8	44-49
14. Hot springs, geysers, and other subaerial geothermal minerals		61	1	35,50
15. Black/white smoker minerals and other seafloor hydrothermal minerals		32	0	46,51,52
16. Low-T aqueous alteration of Hadean subaerial lithologies (see also [#23])		83	3	35,50
17. Marine authigenic Hadean minerals (see also [#24])		51	1	35
18. Minerals formed by freezing		4	3	53

<u>Stage 4a: Earth's earliest continental crust</u>	<u>> 4.4—3.0</u>	<u>2385</u>	<u>1031</u>	22,23,54-57
<u>Igneous rocks</u>		<u>160</u>	<u>17</u>	
19. Granitic intrusive rocks		143	15	22,23,58
20. Acidic volcanic rocks		45	2	22,23,59
<u>Near-surface Processes</u>		<u>1113</u>	<u>244</u>	
21. Chemically precipitated carbonate, phosphate, iron formations		79	3	28,60-67
22. Hydration and low-T subsurface aqueous alteration (see also [#23])		247	85	37,38,68-70
23. Subaerial aqueous alteration by non-redox-sensitive fluids (see also [#47])		398	79	71
24. Authigenic minerals in terrestrial sediments (see also [#17])		74	0	35,71,72
25. Evaporites (prebiotic)		210	65	57,62,73
26. Hadean detrital minerals		250	7	74
27. Radioactive decay; auto-oxidation		9	0	75-77
28. Photo-alteration, pre-biotic		10	0	78
29. Lightning-generated minerals		7	0	34,79-81
30. Terrestrial impact minerals		16	5	82,83
<u>High-T alteration and/or metamorphism</u>		<u>1505</u>	<u>770</u>	
31. Thermally altered carbonate, phosphate, and iron formations		356	89	28,60-66
32. Ba/Mn/Pb/Zn deposits, including metamorphic deposits		412	185	40,68,84
33. Minerals deposited by hydrothermal metal-rich fluids (see also [#12])		797	496	37-43
<u>Stage 4b: Highly evolved igneous rocks</u>	<u>> 3.0</u>	<u>1476</u>	<u>662</u>	
34. Complex granite pegmatites		564	238	85-88
35. Ultra-alkali and agpaitic igneous rocks		726	377	89,90
36. Carbonatites, kimberlites, and related igneous rocks		291	40	40,91-97
37. Layered igneous intrusions and related PGE minerals		135	7	40,98-100
<u>Stage 5: Initiation of plate tectonics</u>	<u>< 3.5—2.5</u>	<u>458</u>	<u>56</u>	101-107
38. Ophiolites		108	7	108-111
39. High-P metamorphism (blueschist, eclogite, ultrahigh P facies)		70	12	112-118

40. Regional metamorphism (greenschist, amphibolite, granulite facies)		319	36	117,118
41. Mantle metasomatism		16	1	119,120
42. Sea-floor Mn nodules		15	0	121-123
43. Shear-induced minerals (including mylonite/slickensides)		9	0	124,125
<i>Stage 6: Anoxic biosphere</i>	<u>< 4.0</u>			
44. Anoxic microbially-mediated minerals (see also [#44])		11	0	126-141
<i>Stage 7: Great Oxidation Event</i>	<u>< 2.4</u>	<u>2328</u>	<u>1298</u>	142-147
45. Oxidized fumarolic minerals (see also [#11])		<u>424</u>	<u>168</u>	34,36
a. [Sulfates, arsenates, selenates, antimonates]		[253]	[116]	
b. [Other oxidized fumarolic minerals]		[276]	[108]	
46. Near-surface hydrothermal alteration of minerals (see also [#22])		52	11	37,38,148
47. Low-T subaerial oxidative hydration, weathering (see also [#16] & [#23])		<u>1998</u>	<u>1119</u>	148
a. [Near-surface hydration of prior minerals]		[1649]	[956]	
b. [Sulfates and sulfites]		[409]	[185]	
c. [Carbonates, phosphates, borates, nitrates]		[577]	[338]	
d. [Arsenates, antimonates, selenates, bismuthinates]		[505]	[361]	
e. [Vanadates, chromates, manganates]		[372]	[229]	
f. [Uranyl (U ⁶⁺) minerals]		[236]	[173]	149,150
g. [Halogen-bearing surface weathering minerals]		[236]	[121]	
h. [Near-surface oxidized, dehydrated minerals]		[316]	[176]	
i. [Terrestrial weathering of meteorites]		[28]	[10]	11
<i>Stage 8: "Intermediate Ocean" (no new paragenetic modes)</i>	1.9—0.9	0	0	151-155
<i>Stage 9: "Snowball Earth" (no new paragenetic modes)</i>	0.9—0.6	0	0	156-158
<i>Stage 10a: Neoproterozoic oxygenation/terrestrial biosphere</i>	< 0.6	<u>597</u>	<u>72</u>	
48. Soil leaching zone minerals	< 0.6	71	4	159-166
49. Oxic cellular biomineralization (see also [#44])	< 0.54	77	1	136,167-186

50. Coal and/or oil shale minerals	< 0.36	273	4	187,188
51. Pyrometamorphic minerals (see also [#54] & [#56])	< 0.36	128	32	34,189,190
52. Guano- and urine-derived minerals	< 0.4	72	17	191,192
53. Other minerals with taphonomic origins	< 0.4	117	14	193,194
<i>Stage 10b: Anthropogenic minerals</i>	< 10 Ka	<u>603</u>	<u>11</u>	195-199
54. Coal and other mine fire minerals (see also [#51] & [#56])		234	6	34,200-202
55. Anthropogenic mine minerals		264	5	197
56. Slag and smelter minerals (see also [#51] & [#55])		143	0	34,197,203-204
57. Other minerals formed by human processes		49	0	195-199, 205,206

* The 10 stages of mineral evolution refer to temporal divisions, as outlined in Table 1 of Hazen et al. (2008). The 57 paragenetic modes are designated by [#1] to [#57].

** Numbers of species are based on paragenetic modes identified for 5659 IMA-approved mineral species, as tabulated on <https://rruff.info/ima> (accessed 23 November 2020).

*** Numbers of species known to form only by that paragenetic mode.

**** **References:** General references for mineral paragenetic modes include Anthony et al. (1990-2003); Deer et al. (1982-2013); and <https://rruff.info/ima> and <https://mindat.org>, and references therein (accessed 17 March 2021).

Numbered references: 1 = Hazen & Morrison (2020); 2 = Zinner (2014); 3 = Nittler & Ciesla (2016); 4 = Boujibar et al. (2021); 5 = Whittet (2003); 6 = Gibb et al. (2004); 7 = Morrison & Hazen (2020); 8 = MacPherson (2014); 9 = Krot et al. (2004); 10 = El Goresy et al. (2002); 11 = Rubin & Ma (2021); 12 = Brearley & Jones (1998); 13 = Krot et al. (2014); 14 = Russell et al. (2018); 15 = Hazen et al. (2021); 16 = Mittlefehldt et al. 1998; 17 = Mittlefehldt (2014); 18 = Morrison & Hazen (2021); 19 = McSween et al. (1988); 20 = Hazen & Morrison (2021); 21 = Tomioka & Miyahara (2017); 22 = Rollinson (2007b); 23 = Van Kranendonk et al. (2007b); 24 = Papineau (2010); 25 = Hazen (2013); 26 = Morrison et al. (2018); 27 = Korenaga (2021); 28 = Isley & Abbott (1999); 29 = O'Neil et al. (2008); 30 = Ashwal (1993); 31 = Prokoph et al. (2004); 32 = O'Neil et al. (2008); 33 = Ernst (2014); 34 = Grapes (2006); 35 = Deer et al. (2004); 36 = Vergasova & Filatov (2016); 37 = Heinrich and Henley (1989); 38 = Pirajno (2009); 39 = Laznicka 1973; 40 = Meyer (1988); 41 = Groves et al. (2005); 42 = Huston et al. (2010); 43 = Jenkin et al. (2015); 44 = Blais & Auvray (1990); 45 = Lowell & Rona (2002); 46 = Palandri & Reed (2004); 47 = Shrenk et al. (2013); 48 = Holm et al. (2015);

49 = Menez et al. (2018); 50 = Wilson (2013); 51 = Hekinian et al. (1980); 52 = Haymon and Kastner (1981); 53 = Genceli Güner et al. (2013); 54 = Wilde et al. (2001); 55 = Kemp & Hawkesworth (2003); 56 = Kemp et al. (2007); 57 = Johnson et al. (2017); 58 = Chappell & White (2001); 59 = Sugitani et al. (2003); 60 = Falkowski et al. 2000; 61 = Klein (2005); 62 = Button (1982); 63 = Anbar & Holland (1992); 64 = Bekker et al. (2010); 65 = Barturin & Bezrukov (1979); 66 = Delaney (1998); 67 = Crevello et al. (1989); 68 = Post (1999); 69 = Savage et al. (1987); 70 = Nishimoto & Yoshido (2010); 71 = Chang et al. (1996); 72 = Holland & Rye (1997); 73 = Buick & Dunlop (1990); 74 = Baker (1962); 75 = Frondel (1958); 76 = Finch & Murakami (1999); 77 = Hazen et al. (2009); 78 = Kim et al. (2013); 79 = Essene & Fisher (1986); 80 = Pasek et al. (2012); 81 = Hess et al. (2021); 82 = Tomioka & Miyahara (2017); 83 = Tschauner (2019); 84 = Leach et al. (2010); 85 = London (2008); 86 = Tkachev (2011); 87 = Grew et al. (2017); 88 = Grew et al. (2019); 89 = Marks & Markl (2017); 90 = Mikhailova et al. (2019); 91 = Patchett et al. (1982); 92 = Bell (1989); 93 = Downes et al. (2012); 94 = Jones et al. (2013); 95 = Mitchell et al. (2019); 96 = Woolley & Kjarsgaard (2008); 97 = Heaman et al. (2019); 98 = Naldrett et al. (1987); 99 = Maier & Groves (2011); 100 = Zientek (2012); 101 = Stern (2005); 102 = Rollinson (2007a); 103 = Condie & Pease (2008); 104 = Shirey et al. (2008); 105 = Shirey and Richardson (2011); 106 = Bauer et al. (2020); 107 = Reimink et al. (2019); 108 = Bai et al. (2011); 109 = Moores (2002); 110 = Dilek (2003); 111 = Furnes et al. (2007); 112 = Chopin (1984); 113 = Hacker (2006); 114 = Palin and White (2016); 115 = Zheng and Chen (2017); 116 = Brown (2007); 117 = Philpotts & Ague (2009); 118 = Vernon (2008); 119 = Luth (2003); 120 = O'Reilly and Griffin (2012); 121 = Hlawatsch et al. (2002); 122 = Fike et al. (2006); 123 = Wegorzewski & Kuhn (2014); 124 = Passchier & Trouw (2005); 125 = Trouw et al. (2009); 126 = Van Kranendonk et al. (2003); 127 = Akai et al. (1999); 128 = Allwood et al. (2006); 129 = Anbar & Holland (1992); 130 = Banerjee (1971); 131 = Frankel & Bazylnski (2003); 132 = Grotzinger & Knoll (1999); 133 = Konhauser et al. (2005); 134 = Kappler et al. (2005); 135 = Schulz & Schulz (2005); 136 = Southam & Saunders (2005); 137 = Lepot et al. (2008); 138 = Marshall (1979); 139 = Burnett & Riggs (1990); 140 = Chauhan (1979); 141 = Cook & Shergold (1990); 142 = Sverjensky & Lee (2010); 143 = Hazen (2015); 144 = Jabłońska & Tawfik (2021); 145 = Canfield (2014); 146 = Lyons et al. (2014); 147 = Anbar et al. (2007); 148 = Anthony et al. (1990-2003); 149 = Nash et al. (1981); 150 = Hazen et al. (2009); 151 = Brasier (1998); 152 = Buick et al. (1995); 153 = Anbar & Knoll (2002); 154 = Brasier (2012); 155 = Mukherjee et al. (2018); 156 = Kirschvink (1992); 157 = Hoffman et al. (1998); 158 = Bodiselitsch et al. (2005); 159 = Johnson and Watson-Stegner (1987); 160 = Holland and Rye (1997); 161 = Rye and Holland (1998); 162 = Retallack (2001); 163 = Kennedy et al. (2006); 164 = Ueshima & Tazaki (1998); 165 = Helgren and Butzer (1977); 166 = Hill et al. (2000); 167 = Yoder (2002); 168 = Dove et al. (2003); 169 = Dove (2010); 170 = Lowenstam & Weiner 1989; 171 = Ensikat et al. (2016); 172 = Endo et al. (2018); 173 = Lichtenegger et al.

(2002); 174 = Zuzuki & Banfield (1999); 175 = Wufuer et al. (2017); 176 = Beazley et al. (2017); 177 = Berg et al. (2020); 178 = Pósfai et al. (2013); 179 = Uebe and Schöler (2016); 180 = Kelm et al. (2015); 181 = Reith et al. (2009); 182 = Li & Gadd (2017); 183 = Cron et al. (2019); 184 = Carmichael & Bräuer (2015); 185 = Weiner & Wagner (1998); 186 = Kattimani et al. (2016); 187 = Saxby (2000); 188 = Schweinfurth (2016); 189 = Gross (1977); 190 = Sokol et al. (2008); 191 = Audra et al. (2017); 192 = Audra et al. (2018); 193 = Behrensmeier et al. (2000); 194 = Mustoe (2018); 195 = Cathcart (2011); 196 = Corcoran et al. (2014); 197 = Hazen et al. (2017); 198 = Hazen & Zalaziewski (2019); 199 = Zeng et al. (2020); 200 = Lapham et al. (1980); 201 = Kruszewski (2013); 202 = Stracher et al. (2015); 203 = Sueoka & Sakakibara (2013); 204 = Kierczak & Ettl (2021); 205 = Merlino & Sartori (1970); 206 = Smith & Prior (1899)

***** Includes 7 interstellar ice phases that are not IMA-approved mineral species.
