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OUTLOOKS IN EARTH AND PLANETARY MATERIALS

On the mineralogy of the "Anthropocene Epoch"

ROBERT M. HAZEN[1,*], EDWARD S. GREW[2], MARCUS J. ORIGLIERI[3], AND ROBERT T. DOWNS[3]

[1]Geophysical Laboratory, Carnegie Institution for Science, 5251 Broad Branch Road NW, Washington, D.C. 20015, U.S.A.
[2]School of Earth and Climate Sciences, University of Maine, Orono, Maine 04469, U.S.A.
[3]Department of Geosciences, University of Arizona, 1040 East 4th Street, Tucson, Arizona 85721-0077, U.S.A.

ABSTRACT

The "Anthropocene Epoch" has been proposed as a new post-Holocene geological time interval—a period characterized by the pervasive impact of human activities on the geological record. Prior to the influence of human technologies, the diversity and distribution of minerals at or near Earth's surface arose through physical, chemical, and/or biological processes. Since the advent of human mining and manufacturing, particularly since the industrial revolution of the mid-eighteenth century, mineral-like compounds have experienced a punctuation event in diversity and distribution owing to the pervasive impact of human activities. We catalog 208 mineral species approved by the International Mineralogical Association that occur principally or exclusively as a consequence of human processes. At least three types of human activities have affected the diversity and distribution of minerals and mineral-like compounds in ways that might be reflected in the worldwide stratigraphic record. The most obvious influence is the widespread occurrence of synthetic mineral-like compounds, some of which are manufactured directly for applications (e.g., YAG crystals for lasers; Portland cement) and others that arise indirectly (e.g., alteration of mine tunnel walls; weathering products of mine dumps and slag). A second human influence on the distribution of Earth's near-surface minerals relates to large-scale movements of rocks and sediments—sites where large volumes of rocks and minerals have been removed. Finally, humans have become relentlessly efficient in redistributing select natural minerals, such as gemstones and fine mineral specimens, across the globe. All three influences are likely to be preserved as distinctive stratigraphic markers far into the future.

Keywords: Mineral evolution, archeology, new minerals, mining, philosophy of mineralogy, sociology of mineralogy, Anthropocene Epoch

INTRODUCTION

Do humans play a significant role in Earth's mineral evolution? In the earliest analyses of Earth's changing mineralogy through deep time (Zhabin 1979, 1981; Yushkin 1982; Hazen et al. 2008; Hazen and Ferry 2010; Krivovichev 2013), the influences of human activities received only peripheral mention. The 10 stages of mineral evolution proposed by Hazen et al. (2008) relate only to pre-technological physical, chemical, and biological processes. Nevertheless, questions related to human influences on Earth's mineralogy remain of interest and importance. In comments on publications, as well as in discussions following seminars on mineral evolution, one of the most frequent questions has been whether we are now in "Stage 11"—a time when mineral diversity is experiencing a punctuation event owing to the pervasive near-surface effects of human industrial society. In this contribution we consider the nature and implications of "Anthropocene mineralogy."

Although yet to be confirmed by the International Union of Geological Sciences, there is growing advocacy for formal recognition of the "Anthropocene Epoch," the successor of the Holocene Epoch, to characterize the present time within the Quaternary Period (e.g., Zalasiewicz et al. 2008; Waters et al. 2016; however, see Finney and Edwards 2016 for a contrary view). The Anthropocene Epoch, based on terminology proposed many decades ago (e.g., Steffen et al. 2011 and references therein), would be defined as commencing when human activities began to have a significant impact on Earth's near-surface environment on a global scale, including the atmosphere, oceans, and sediments. Opinions differ regarding the most appropriate starting date for the Anthropocene Epoch. Some scholars have suggested a time associated with the advent of near-surface mining and smelting technologies in classic times (e.g., Ruddiman 2003; Smith and Zeder 2013), although such alterations of Earth's surface were not global in scale. Others promote a starting date correlating with the industrial revolution of the eighteenth century, when widespread burning of carbon-based fuels led to an increase in atmospheric CO_2 (Zalasiewicz et al. 2008; Edgeworth et al. 2015; Ellis et al. 2013; Lewis and Maslin 2015). Alternatively, several geochemists have recently advocated 1950 as the starting year, based on pervasive worldwide isotopic markers related to nuclear weapons testing programs (Zalasiewicz et al. 2015).

Whatever the specific starting date, an important aspect of characterizing the Anthropocene Epoch is achieving an understanding of human influences on the diversity and distribution of minerals and mineral-like compounds. This question of "Anthropocene mineralogy" has been addressed by Zalasiewicz et al. (2013), who focus on the fascinating question of the impacts that present-day human activities might have on the stratigraphic

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* E-mail: rhazen@ciw.edu

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record of the Anthropocene Epoch. In particular, what synthetic mineral-like compounds, such as durable metal alloys, carbide abrasives, and laser crystals, might be preserved as distinctive marker compounds in the distant future? In the contribution of Zalasiewicz et al. (2013), which appeared as part of a more comprehensive analysis of Anthropocene stratigraphy (Waters et al. 2013) sponsored by the Geological Society (London), they argue that mineral-like phases synthesized by humans are pervasive, that they constitute distinctive stratigraphic markers for the Anthropocene Epoch, and that they deserve more detailed mineralogical consideration. They conclude: “The growing geological and societal significance of this phenomena is now great enough for human-made minerals to be formally listed and catalogued by the IMA.”

The formal definition of a mineral lies at the heart of this discussion. Nickel and Grice (1998), citing Nickel (1995a) on behalf of the Commission on New Minerals and Mineral Names of the International Mineralogical Association (now Commission on New Minerals, Nomenclature and Classification, abbreviated to IMA CNMNC), defined a mineral as “a naturally occurring solid that has been formed by geological processes, either on Earth or in extraterrestrial bodies.” It has long been recognized that many minerals have also been synthesized, although the mineral name need not reflect the name of the synthetic equivalent. Nickel (1995b) underscores the opinion that “mineral names should be given only to naturally occurring substances.” Thus, the synthetic products of human industry and commerce, even those that might be preserved for millions of years in the stratigraphic record, are not currently the purview of the IMA CNMNC and consequently are not recognized as minerals (though there is nothing to prevent a more detailed and thoughtful cataloging of such compounds as a supplement to lists of minerals).

Zalasiewicz et al. (2013) did not consider a more ambiguous category of mineral-like compounds that include what might be termed “human-mediated minerals”—crystalline compounds that form indirectly by natural physical, chemical, and biological processes, but as an inadvertent consequence of human modifications to the environment. The IMA Commission has addressed this question in some detail (see Text Box 1). Their statement highlights the varied and nuanced character of mineral-like substances that arise in part or in toto by human activities. Given the increased recognition of, and interest in, human influences on Earth’s near-surface environment, we feel that a more comprehensive understanding and analysis of the mineralogical nature of the Anthropocene Epoch is warranted.

Another contentious issue is whether substances formed by the action of air or water on anthropogenic substances should be regarded as minerals. A well-known example is that of the Laurium “minerals” formed by the reaction of seawater with ancient metallurgical slags. A potential problem with accepting similar products as minerals in the modern age is that a multitude of unusual substances could be created purposely by exposing exotic man-made materials to the influence of weathering agents, and it would not be appropriate to give such substances the same status as minerals formed entirely by geological processes. It was therefore decided that substances formed from man-made materials by geological agents should not be accepted as minerals in the future (Nickel 1995a). However, the exclusion of such substances from the mineral lexicon does not preclude their description as artificial substances.

IMA statement on “anthropogenic substances” (from Nickel and Grice 1998):

Anthropogenic substances, i.e., those made by Man, are not regarded as minerals. However, there are other cases in which human intervention in the creation of a substance is less direct, and the borderline between mineral and non-mineral can be unclear. One such case is the occurrence of new substances that owe their origin, at least in part, to human activities such as mining or quarrying. If such substances are formed purely as a result of the exposure of existing rock or minerals to the atmosphere or to the effects of groundwater, they can generally be accepted as minerals. However, if their occurrence is due, at least in part, to the interaction of existing minerals with substances of non-geological origin such as blasting powder, corroded human artifacts, or industrially contaminated water, then such products are not to be regarded as minerals.

Substances formed by combustion are not generally regarded as minerals. A contentious issue is the occurrence of substances in the combustion products of coal mines, waste dumps, or peat bogs. The origin of a particular fire is often difficult to determine, and therefore the possibility of human intervention cannot be entirely eliminated, nor can the possibility of human artifacts contributing to the combustion products. It has therefore been decided that, as a general rule, products of combustion are not to be considered as minerals in the future.

Substances that would not be accepted as minerals according to the above criteria, but which have been accepted in the past, are not to be automatically discredited as a result of the new rulings, as it is not our intention to roll back the clock but rather to establish guidelines for the future.

In particular, we focus on two aspects of what might be termed “Anthropocene mineralogy”—the distinctive changes, most notably increases in the diversity and changes in the near-surface distribution of minerals and mineral-like phases, associated with human activities. First, we consider mineral diversity by exploring several different types of human-mediated mineral-like compounds—both by directed synthesis and by indirect or secondary natural processes—and proposing a taxonomy for these phases. We catalog two broad types of such compounds: (1) phases from the more than 5100 approved IMA CNMNC mineral species that occur exclusively or predominantly as an inadvertent consequence of human activities (Table 1), and (2) examples of synthetic mineral-like phases (Table 2), many of which are not known to occur naturally.

Second, we consider how human activities have altered the distribution of naturally occurring minerals in Earth’s near-surface environment, most notably through large-scale movements of rocks and sediments as a consequence of mining operations and the construction of cities, waterways, and roads.

We conclude by returning to the important question of

Table 1a. List of minerals reported exclusively as human-mediated phases with no confirmed natural occurrences

	Number of localities	Formula	Type locality; other localities	Reference(s)
I. Mine-associated (“post-mine”) minerals				
		A. Alteration phases recovered from ore dumps		
Delrioite	3	$Sr(V^{5+}O_3)_2 \cdot 4H_2O$	Jo Dandy mine, Paradox Valley, Montrose County, Colorado	Thompson and Sherwood (1959)
Metadelrioite	2	$SrCa(VO_3)_2(OH)_2$	Jo Dandy mine, Paradox Valley, Montrose County, Colorado	Smith (1970)
Rosièresite (questionable species)	2	$Pb_xCu_yAl_z(PO_4)m \cdot nH_2O$	Rosières, Carmaux, France; Huelgoat, Finistère, France	Berthier (1841); Lacroix (1910)
Schuetteite	15	$Hg_3O_2(SO_4)$	Ocean mine dump, San Luis Obispo County, California	Bailey et al. (1959)
Smrkovecite	2	$Bi_2O(PO_4)(OH)$	Smrkovec, Czech Republic	Řídkošil et al. (1996)
Wheatleyite	1	$Na_2Cu(C_2O_4)_2 \cdot 2H_2O$	Wheatley mines, Chester County, Pennsylvania	Rouse et al. (1986)
Widgiemoolthalite	1	$Ni_5(CO_3)_4(OH)_2 \cdot 4–5H_2O$	132 North mine, Widgiemooltha, Australia	Nickel et al. (1993)
		B. Alteration phases associated with mine tunnel walls		
Adolfpateraite	1	$K(UO_2)(SO_4)(OH) \cdot H_2O$	Jáchymov, western Bohemia, Czech Republic	Plášil et al. (2012)
Albrechtschraufite	1	$Ca_4Mg(UO_2)_2(CO_3)_6F2 \cdot 17H_2O$	Jáchymov, western Bohemia, Czech Republic	Mereiter (2013)
Alwilksinite-(Y)	1	$Y(UO_2)_3(SO_4)_2O(OH)_3 \cdot 14H_2O$	Blue Lizard mine, San Juan County, Utah	Kampf et al. (2016a)
Apexite	1	$NaMg(PO_4) \cdot 9H_2O$	Apex mine, Austin, Lander County, Nevada	Kampf et al. (2015c)
Běhounekite	1	$U^{4+}(SO_4)_2 \cdot 4H_2O$	Jáchymov, western Bohemia, Czech Republic	Plášil et al. (2011a)
Belakovskiite	1	$Na_7(UO_2)(SO_4)_4(SO_3OH) \cdot 3H_2O$	Blue Lizard mine, San Juan County, Utah	Kampf et al. (2014a)
Bluelizardite	1	$Na_7(UO_2)(SO_4)_4Cl \cdot 2H_2O$	Blue Lizard mine, San Juan County, Utah	Plášil et al. (2014a)
Bobcookite	1	$NaAl(UO_2)_2(SO_4)_4 \cdot 18H_2O$	Blue Lizard mine, San Juan County, Utah	Kampf et al. (2015a)
Calciodelrioite	3	$Ca(VO_3)_2 \cdot 4H_2O$	West Sunday mine, Slick Rock District, San Miguel County, Colorado	Kampf et al. (2012b)
Canavesite	2	$Mg_2(HBO_3)(CO_3) \cdot 5H_2O$	Brosso mine, Piedmont, Italy	Ferraris et al. (1978)
Cobaltoblödite	1	$Na_2Co(SO_4)_2 \cdot 4H_2O$	Blue Lizard mine, San Juan County, Utah	Kasatkin et al. (2013)
Cobaltzippeite	2	$Co(UO_2)_2(SO_4)O_2 \cdot 3.5H_2O$	Happy Jack mine, San Juan County, Utah	Frondel et al. (1976)
Fermiite	1	$Na_4(UO_2)(SO_4)_3 \cdot 3H_2O$	Blue Lizard mine, San Juan County, Utah	Kampf et al. (2015b)
Gatewayite	1	$Ca_6(As^{3+}V_3^{4+}V_9^{5+}As_6^{5+}O_{51}) \cdot 31H_2O$	Packrat mine, Gateway District, Mesa County, Colorado	Kampf et al. (2015d)
Geschieberite	1	$K_2(UO_2)(SO_4)_2 \cdot 2H_2O$	Jáchymov, western Bohemia, Czech Republic	Plášil et al. (2015a)
Gunterite	1	$Na_4(H_2O)_{16}(H_2V_{10}O_{28}) \cdot 6H_2O$	Sunday mine, Slick Rock District, San Miguel County, Colorado	Kampf et al. (2011a)
Hughesite	3	$Na_3AlV_{10}O_{28} \cdot 22H_2O$	Sunday mine, Slick Rock District, San Miguel County, Colorado	Rakovan et al. (2011)
Jáchymovite	3	$(UO_2)_8(SO_4)(OH)_{14} \cdot 13H_2O$	Jáchymov, western Bohemia, Czech Republic	Čejka et al. (1996)
Ježekite	1	$Na_8[(UO_2)(CO_3)_3](SO_4)_2 \cdot 3H_2O$	Jáchymov, western Bohemia, Czech Republic	Plášil et al. (2015b)
Kegginite	1	$Pb_3Ca_3[AsV_{12}O_{40}(VO)] \cdot 20H_2O$	Packrat mine, Gateway District, Mesa County, Colorado	Kampf et al. (2016e)
Klaprothite	1	$Na_6(UO_2)(SO_4)_4 \cdot 4H_2O$	Blue Lizard mine, San Juan County, Utah	Kampf et al. (2016b)
Kokinosite	1	$Na_2Ca_2(V_{10}O_{28}) \cdot 24H_2O$	St. Jude mine, Slick Rock District, San Miguel County, Colorado	Kampf et al. (2014d)
Línekite	1	$K_2Ca_3[(UO_2)(CO_3)_3]_2 \cdot 7H_2O$	Jáchymov, western Bohemia, Czech Republic	Plášil et al. (2013a)
Magnesiozippeite	>4	$Mg(UO_2)_2(SO_4)O_2 \cdot 3.5H_2O$	Lucky Strike No.2 mine, Emery County, Utah	Frondel et al. (1976)
Manganoblödite	2	$Na_2Mn(SO_4)_2 \cdot 4H_2O$	Blue Lizard mine, San Juan County, Utah	Kasatkin et al. (2013)
Marécottite	1	$Mg_3O_6(UO_2)_8(SO_4)_4(OH)_2 \cdot 28H_2O$	La Creusaz deposit, Valais, Switzerland	Brugger et al. (2003)
Mesaite	1	$CaMn_5^{2+}(V_2O_7)_3 \cdot 12H_2O$	Packrat mine, Gateway District, Mesa County, Colorado	Kampf et al. (2015e)
Mathesiusite	1	$K_5(UO_2)_4(SO_4)_4(VO_5) \cdot 4H_2O$	Jáchymov, western Bohemia, Czech Republic	Plášil et al. (2014b)
Meisserite	1	$Na_5(UO_2)(SO_4)_3(SO_3OH) \cdot H_2O$	Blue Lizard mine, San Juan County, Utah	Plášil et al. (2013b)
Metamunirite	10	$NaV^{5+}O_3$	Burro mine, Slick Rock district, San Miguel County, Colorado	Evans (1991)
Morrisonite	1	$Ca_{11}(As^{3+}V_2^{4+}V_{10}^{5+}As_6^{5+}O_{51})_2 \cdot 78H_2O$	Packrat mine, Gateway District, Mesa County, Colorado	Kampf et al. (2015f)
Nickelzippeite	5	$Ni_2(UO_2)_6(SO_4)_3(OH)_{10} \cdot 16H_2O$	Happy Jack mine, San Juan County, Utah	Frondel et al. (1976)
Oppenheimerite	1	$Na_2(UO_2)(SO_4)_2 \cdot 3H_2O$	Blue Lizard mine, San Juan County, Utah	Kampf et al. (2015b)
Ottohahnite	1	$Na_2(UO_2)(SO_4)_2 \cdot 3H_2O$	Blue Lizard mine, San Juan County, Utah	Kampf et al. (2016c)
Packratite	1	$Ca_{11}(As^{3+}V_{10}^{5+}V_2^{4+}As_6^{5+}O_{51})_2 \cdot 83H_2O$	Packrat mine, Gateway District, Mesa County, Colorado	Kampf et al. (2014e)
Péligotite	1	$Na_6(UO_2)(SO_4)_4 \cdot 4H_2O$	Blue Lizard mine, San Juan County, Utah	Kampf et al. (2016d)
Plášilite	1	$Na(UO_2)(SO_4)(OH) \cdot 2H_2O$	Blue Lizard mine, San Juan County, Utah	Kampf et al. (2014b)
Pseudojohannite	>6	$Cu_3(UO_2)_4O_4(SO_4)_2(OH)_2 \cdot 12H_2O$	Jáchymov, western Bohemia, Czech Republic	Brugger et al. (2006)
Rakovanite	2	$Na_3H_3V_{10}O_{28} \cdot 15H_2O$	Sunday and West Sunday mines, Slick Rock District, San Miguel County, Colorado	Kampf et al. (2011b)
Schindlerite	1	$(NH_4)_4Na_2(V_{10}^{5+}O_{28}) \cdot 10H_2O$	St. Jude mine, Slick Rock District, San Miguel County, Colorado	Kampf et al. (2013a)
Sejkoraite-(Y)	1	$Y_2[(UO_2)_8O_6(SO_4)_4(OH)_2] \cdot 26H_2O$	Jáchymov, western Bohemia, Czech Republic	Plášil et al. (2011b)
Slavkovite	3	$Cu_{13}(AsO_4)_6(AsO_3OH)_4 \cdot 23H_2O$	Jáchymov, western Bohemia, Czech Republic	Sejkora et al. (2010)
Štěpite	1	$U(AsO_3OH)_2 \cdot 4H_2O$	Jáchymov, western Bohemia, Czech Republic	Plášil et al. (2013c)
Svornostite	1	$K_2Mg[(UO_2)(SO_4)_2]_2 \cdot 8H_2O$	Jáchymov, western Bohemia, Czech Republic	Plášil et al. (2015c)
Vanarsite	1	$NaCa_{12}(As^{3+}V_{8.5}^{5+}V_{3.5}^{4+}As_6^{5+}O_{51})_2 \cdot 78H_2O$	Packrat mine, Gateway District, Mesa County, Colorado	Kampf et al. (2014f)
Vysokýite	1	$U^{4+}[AsO_2(OH)_2]_4 \cdot 4H_2O$	Jáchymov, western Bohemia, Czech Republic	Plášil et al. (2015d)
Wernerbaurite	1	$\{(NH_4)_2[Ca_2(H_2O)_{14}](H_2O)_2\}\{V_{10}^{5+}O_{28}\}$	St. Jude mine, Slick Rock District, San Miguel County, Colorado	Kampf et al. (2013a)

(Continued on next page)

TABLE 1a.—*CONTINUED*

	Number of localities	Formula	Type locality; other localities	Reference(s)
Wetherillite	1	$Na_2Mg(UO_2)_2(SO_4)_4 \cdot 18H_2O$	Blue Lizard mine, San Juan County, Utah	Kampf et al. (2015a)
Zýkaite	7	$Fe^{3+}{}_4(AsO_4)_3(SO_4)(OH) \cdot 15H_2O$	Kaňk, Czech Republic	Čech et al. (1978)
C. Mine water precipitates				
Bluestreakite	1	$K_4Mg_2(V^{4+}_2V^{5+}_8O_{28}) \cdot 14H_2O$	Blue Streak mine, Bull Canyon, Montrose County, Colorado	Kampf et al. (2014c)
Ferrarisite	8	$Ca_5(AsO_3OH)_2(AsO_4)_2 \cdot 9H_2O$	Gabe Gottes mine, Alsace, France	Bari et al. (1980a)
Fluckite	3	$CaMn^{2+}(AsO_3OH)_2 \cdot 2H_2O$	Gabe Gottes mine, Alsace, France	Bari et al. (1980b)
Lannonite	2	$HCa_4Mg_2Al_4(SO_4)_8F_9 \cdot 32H_2O$	Lone Pine Mine, Catron County, New Mexico	Williams and Cesbron (1983)
Magnesiopascoite	4	$Ca_2Mg(V_{10}O_{28}) \cdot 16H_2O$	Blue Cap mine, San Juan County, Utah	Kampf and Steele (2008a)
Martyite	2	$Zn_3V_2O_7(OH)_2 \cdot 2H_2O$	Blue Cap mine, San Juan County, Utah	Kampf and Steele (2008b)
Phosphorrösslerite	3	$Mg(PO_3OH).7H_2O$	Stübibau mine, Schellgaden, Austria	Friedrich and Robitsch (1939)
Postite	2	$MgAl_2(V_{10}O_{28})(OH)_2 \cdot 27H_2O$	Vanadium Queen and Blue Cap mines, San Juan County, Utah	Kampf et al. (2012a)
D. Minerals found in slag or the walls of smelters				
Cetineite	6	$NaK_5Sb_{14}S_6O_{18} \cdot 6H_2O$	Le Cetine mine, Tuscany, Italy	Sabelli and Vezzalini (1987)
Fiedlerite	6	$Pb_3Cl_4F(OH) \cdot H_2O$	Lavrion District slag localities, Greece	Merlino et al. (1994)
Georgiadèsite	2	$Pb_4(As^{3+}O_3)Cl_4(OH)$	Lavrion District slag localities, Greece	Lacroix and de Schulten (1907)
Nealite	4	$Pb_4Fe(AsO_3)_2Cl_4 \cdot 2H_2O$	Lavrion District slag localities, Greece	Dunn and Rouse (1980)
Simonkolleite	8	$Zn_5(OH)_8Cl_2 \cdot H_2O$	Richelsdorf slags, Hesse, Germany	Schmetzer et al. (1985)
Thorikosite	2	$Pb_3O_3Sb^{3+}(OH)Cl_2$	Lavrion District slag localities, Greece	Dunn and Rouse (1985)
E. Minerals associated with mine dump fires, including coal mine dumps				
Acetamide	1	CH_3CONH_2	Dump in a coal mine, L'viv-Volynskii Coal Basin, Ukraine	Srebrodol'skiy (1975)
Bazhenovite	6	$Ca_8S_5(S_2O_3)(OH)_{12} \cdot 20H_2O$	Korkino, Chelyabinsk, Russia	Chesnokov et al. (2008)
Cuprospinel	1	$Cu^{2+}Fe^{3+}_2O_4$	Consolidated Rambler mine, Baie Verte, Newfoundland, Canada	Nickel (1973)
Downeyite	2	SeO_2	Forestville, Schuykill County, Pennsylvania	Finkelman and Mrose (1977)
Guildite	1	$CuFe^{3+}(SO_4)_2(OH) \cdot 4H_2O$	United Verde mine, Yavapai County, Arizona	Lausen (1928)
Hoelite	5	$C_{14}H_8O_2$	Mt. Pyramide, Spitsbergen, Norway	Oftedal (1922)
Kladnoite	3	$C_6H_4(CO)_2NH$	Libušín, Kladno coal basin, Czech Republic	Rost (1942)
Laphamite	1	As_2Se_3	Burnside, Northumberland County, Pennsylvania	Dunn et al. (1986)
Lausenite	3	$Fe^{3+}_2(SO_4)_3 \cdot 5H_2O$	United Verde mine, Yavapai County, Arizona	"rogersite" Lausen (1928)
Svyatoslavite	1	$CaAl_2Si_2O_8$	Coal Mine No. 45, Kopeisk, Russia	Chesnokov et al. (2008)
F. Interaction with mine timbers or leaf litter				
Paceite	1	$CaCu(CH_3COO)_2 \cdot 6H_2O$	Potosi mine, Broken Hill, Australia	Hibbs et al. (2002)
Hoganite	2	$Cu(CH_3COO)_2 \cdot H_2O$	Potosi mine, Broken Hill, Australia	Hibbs et al. (2002)
Nickelboussingaultite	4	$(NH_4)_2Ni(SO_4)_2 \cdot 6H_2O$	Norilsk, Krasnoyarsk Territory, Russia (type)	Yakhontova et al. (1976)
G. Minerals associated with geothermal piping systems				
Ammonioborite	1	$(NH_4)_3B_{15}O_{20}(OH)_8 \cdot 4H_2O$	Larderello, Tuscany, Italy	Schaller (1933); Ciriotti et al. (2009)
Biringuccite	1	$Na_2B_5O_8(OH) \cdot H_2O$	Larderello, Tuscany, Italy	Cipriani and Vannuccini (1961); Ciriotti et al. (2009)
Nasinite	1	$Na_2B_5O_8(OH) \cdot 2H_2O$	Larderello, Tuscany, Italy	Cipriani and Vannuccini (1961); Ciriotti et al. (2009)
II. Miscellaneous human-mediated minerals				
A. Minerals associated with alteration of tin archeological artifacts				
Abhurite	7	$Sn^{2+}_{21}O_6(OH)_{14}Cl_{16}$	Sharm Abhur Cove, Saudi Arabia	Matzko et al. (1985)
B. Minerals formed in storage cabinets in museums				
Calclacite		$Ca(CH_3COO)Cl \cdot 5H_2O$	(Grandfathered; no natural localities)	Van Tassel (1945)
C. Allegedly from placers, possibly a hoax				
Jedwabite	1	Fe_7Ta_3	Nizhnii Tagil, Middle Urals, Russia	Pekov (1998)
Niobocarbide	1	NbC	Nizhnii Tagil, Middle Urals, Russia	Pekov (1998)
Tantalcarbide	1	TaC	Nizhnii Tagil, Middle Urals, Russia	Pekov (1998)

Notes: All listed minerals were approved by the IMA CNMNC. Numbers of localities are estimated from http://mindat.org in early 2016.

Zalasiewicz et al. (2013): if one were to revisit Earth in tens of millions of years, what stratigraphic evidence might be preserved in the form of the modified diversity and distribution of minerals and mineral-like compounds to provide unambiguous markers for Earth's "Anthropocene Epoch"?

Taxonomy of human-mediated mineral-like compounds

Minerals are by definition naturally occurring compounds formed by geological processes. Strictly speaking, the term "natural" means compounds formed without any human intervention, i.e., minerals are those compounds that would form in the absence of humankind. Human activities can lead to the production of varied mineral-like compounds, both intentionally through directed synthesis and inadvertently as alteration products following commercial activities. Although the distinction between strictly natural processes and processes involving human activity, i.e., anthropogenic, can be simply stated, pinpointing the distinction in some cases can be difficult. Accordingly, we consider two broad categories of human-mediated mineral-like compounds. Table 1 lists 208 IMA CNMNC-approved minerals that have been reported either exclusively as inadvertent byproducts of human

TABLE 1b. List of minerals interpreted to have been produced inadvertently by human processes or through human mediation at one or more localities, as well as reported to occur naturally (OK) or suspected to occur naturally (?) at other localities

Name (Localities)	Formula	Locality for anthropogenic mineral (reference)	Natural	Locality for natural mineral (reference)
I. Mine-associated ("post-mine") minerals				
		A. Alteration phases recovered from dumps, including ore and serpentinite		
Bernalite	$Fe(OH)_3$	Taxco, Guerrero, Mexico in tailings (Mendoza et al. 2005)	?	
Boyleite	$ZnSO_4\cdot 4H_2O$	Mole River mine, northern New South Wales, Australia in dump (Ashley and Lottermoser 1999)	?	
Gunningite	$ZnSO_4\cdot H_2O$	Comstock-Keno mine, Yukon, Canada (type) - post mine and dump (Jambor and Boyle 1962)	?	
Hydromagnesite	$Mg_5(CO_3)_4(OH)_2\cdot 4H_2O$	Clinton Creek chrysotile deposit, Yukon Territory, Canada (Wilson et al. 2006)	OK	Castle Point, Hoboken, Hudson County, New Jersey, U.S.A. (type) (Wachtmeister 1828)
Kaňkite	$Fe^{3+}AsO_4\cdot 3\cdot 5H_2O$	Kaňk, Czech Republic (type) (Čech et al. 1976)	?	
Krausite	$KFe^{3+}(SO_4)_2\cdot H_2O$	Santa María mine, Velardeña, Durango, Mexico (Foshag 1931)	OK	Sulfur Hole, San Bernardino County, California (type) (Foshag 1931)
Krautite	$Mn^{2+}(AsO_3OH)\cdot H_2O$	Mole River mine, northern New South Wales, Australia in dump (Ashley and Lottermoser 1999)	?	
Lansfordite	$MgCO_3\cdot 5H_2O$	Clinton Creek chrysotile deposit, Yukon Territory, Canada (Wilson et al. 2006)	OK	ODP Site 799 in the Japan Sea (Matsumoto 1992)
Nesquehonite	$MgCO_3\cdot 3H_2O$	Clinton Creek chrysotile deposit, Yukon Territory, Canada (Wilson et al. 2006)	OK	Chondrite Lewis Cliff 8532, Antarctica (Jull et al. 1988)
Orthoserpierite	$Ca(Cu,Zn)_4(SO_4)_2(OH)_6\cdot 3H_2O$	Copper Creek district, Pinal County, Arizona (Shannon 1996) looks anthropogenic from photos	?	
Pharmacolite	$Ca(AsO_3OH)\cdot 2H_2O$	Mole River mine, northern New South Wales, Australia in dump (Ashley and Lottermoser 1999)	OK	Wittichen im Fürstenbergischen, Baden-Württemberg, Germany (type) (Klaproth 1804)
Ramsbeckite	$(Cu,Zn)_{15}(SO_4)_4(OH)_{22}\cdot 6H_2O$	Bastenberg mine, Ramsbeck, Germany (type) (von Hodenberg et al. 1985)	?	
Schulenbergite	$(Cu,Zn)_7(SO_4)_2(OH)_{10}\cdot 3H_2O$	Glücksrad mine, Oberschulenberg, Harz, Germany (type) (von Hodenberg et al. 1984)	OK	Platosa mine, Bermejillo, Durango, Mexico (Moore and Megaw, 2003)
Scorodite	$Fe^{3+}AsO_4\cdot 2H_2O$	Mole River mine, northern New South Wales, Australia in dump (Ashley and Lottermoser 1999)	OK	Torrecillas mine, Chile
Yvonite	$Cu(AsO_3OH)\cdot 2H_2O$	Salsigne mine, Salsigne, France (type) (Sarp and Černý 1998)	?	
		B. Alteration of an exposed ore body		
Huemulite	$Na_4MgV^{5+}_{10}O_{28}\cdot 24H_2O$	Huemul mine, Mendoza, Argentina (type) (Gordillo et al. 1966)	?	
		C. Alteration of mine tunnel walls		
Andersonite	$Na_2Ca(UO_2)(CO_3)_3\cdot 6H_2O$	Hillside mine, Yavapai County, Arizona (type) (Axelrod et al. 1951)	?	
Bayleyite	$Mg_2(UO_2)(CO_3)_3\cdot 18H_2O$	Hillside mine, Yavapai County, Arizona (type) (Axelrod et al. 1951)	?	
Bianchite	$(Zn,Fe^{2+})(SO_4)\cdot 6H_2O$	Raibl mines, Tarvisio, Italy (type) (Andreatta 1930)	?	
Coquimbite	$Fe^{3+}_2(SO_4)_3\cdot 9H_2O$	incrustation on mine walls, Copper Queen mine, Bisbee, Arizona (Merwin and Posnjak 1937)	OK	Alum Grotto, Vulcano, Italy (Demartin et al. 2010)
Goslarite	$ZnSO_4\cdot 7H_2O$	Rammelsberg mine, Goslar, Germany (type) (Palache et al. 1951)	OK	"Vienna Woods" hydrothermal field, Manus Basin, Bismark Sea, Papua New Guinea (Steger 2015)
Kornelite	$Fe^{3+}_2(SO_4)_3\cdot 7H_2O$	incrustation on mine walls, Copper Queen mine, Bisbee, Arizona (Merwin and Posnjak 1937)	?	
Dietrichite	$ZnAl_2(SO_4)_4\cdot 22H_2O$	Baia Sprie mine, Romania (type) (Schroeckinger 1878)	?	
Natrozippeite	$Na_5(UO_2)_8(SO_4)_4O_5(OH)_3\cdot 12H_2O$	Happy Jack mine, Emery County, Utah (type of redefined) (Frondel et al. 1976)	?	
Pascoite	$Ca_3V^{5+}_{10}O_{28}\cdot 17H_2O$	Ragra mine, Pasco Province, Peru (type) (Hillebrand et al. 1914)	?	
Picropharmacolite	$Ca_4Mg(AsO_3OH)_2(AsO_4)_2\cdot 11H_2O$	Richelsdorf mine, Hesse, Germany (type) (Pierrot 1961)	?	
Swartzite	$CaMg(UO_2)(CO_3)3\cdot 12H_2O$	Hillside mine, Yavapai County, AZ (type) (Axelrod et al. 1951)	?	
Uranopilite	$(UO_2)_6SO_4O_2(OH)_6\cdot 14H_2O$	Jáchymov, western Bohemia, Czech Republic) (Frondel 1952; Burns 2001	?	
Zdeněkite	$NaPbCu_5(AsO_4)_4Cl\cdot 5H_2O$	Cap Garonne mine, Le Pradet, France (type) (Chiappero and Sarp 1995)	?	
Znucalite	$CaZn_{11}(UO_2)(CO_3)_3(OH)_{20}\cdot 4H_2O$	Lill mine, Příbram, Czech Republic (type) (Ondruš et al. 1990)	?	
		D. Minerals found in slag or the walls of smelters		
Boleite	$KAg_9Pb_{26}Cu_{24}Cl_{62}(OH)_{48}$	Lavrion slag localities, Greece (Gelaude et al. 1996)	OK	Boleo, Baja California Sur, Mexico (type) (Mallard and Cumenge 1891)
Claringbullite	$Cu^{2+}_4FCl(OH)_6$	Juliushütte, Rammelsberg, Harz, Germany (van den Berg and van Loon 1990)	OK	Nchanga mine, Chingola, Zambia (type) (Fejer et al. 1977)
Cumengeite	$Pb_{21}Cu_{20}Cl_{42}(OH)_{40}\cdot 6H_2O$	Lavrion slag localities, Greece (Gelaude et al. 1996)	OK	Boleo, Baja California Sur, Mexico (type) (Mallard 1893)
Cyanochroite	$K_2Cu(SO_4)_2\cdot 6H_2O$	Lavrion slag localities, Greece (Gelaude et al. 1996)	OK	Monte Somma. Somma-Vesuvio, Naples, Italy (type) (Guarini et al. 1855; Ciriotti et al. 2009)
Elyite	$CuPb_4(SO_4)\ O_2(OH)_4\cdot H_2O$	Kall, Eifel, North Rhine-Westphalia, Germany (Blass and Graf 1995)	?	
Glaucocerinite	$Zn_{1-x}Al_x(SO_4)_{x/2}(OH)_2\cdot nH_2O$	Smelter slag localities near Stolberg, Aachen, Germany (Blass and Graf 1993)	?	

(Continued on next page)

Table 1b.—*Continued*

Name (Localities)	Formula	Locality for anthropogenic mineral (reference)	Natural	Locality for natural mineral (reference)
Kapellasite	$Cu_3Zn(OH)_6Cl_2$	Juliushütte, Rammelsberg, Harz Mountains, Germany (Krause et al. 2006)	OK	Sounion No. 19 mine, Kamariza, Lavrion, Greece (Krause et al. 2006)
Ktenasite	$(Cu,Zn)_5(SO_4)_2(OH)_6·6H_2O$	Lavrion slag localities, Greece (Schnorrer-Köhler et al. 1988)	?	
Langite	$Cu_4SO_4(OH)_6·2H_2O$	Lechnerberg slag locality, Kaprun, Hohe Tauern, Salzburg, Austria (Kolitsch and Brandstätter 2009)	?	
Laurionite	$PbCl(OH)$	Thorikos Bay slag locality, Lavrion, Greece (Gelaude et al. 1996)	?	
Lautenthalite	$PbCu_4(SO_4)_2(OH)_6·3H_2O$	Lautenthal Smelter slag, Harz, Mountains, Germany (type) (Medenbach and Gebert1993)	?	
Namuwite	$Zn_4SO_4(OH)_6·4H_2O$	Lavrion slag localities, Greece (Schnorrer-Köhler et al. 1988)	?	
Nitrobarite	$Ba(NO_3)_2$	Slag localities, Waitschach, Hüttenberg, Carinthia, Austria (Kolitsch et al. 2013)	OK	Chile, locality unknown (type) (Groth 1882)
Paralaurionite	$PbCl(OH)$	Lavrion slag localities, Greece (type) (Smith 1899)	?	
Penfieldite	$Pb_2Cl_3(OH)$	Lavrion District slag localities, Greece (type) (Genth 1892)	?	
Posnjakite	$Cu_4SO_4(OH)_6·H_2O$	Richelsdorfer Gebirge slag locality, Germany (Blass and Graf 1993)	?	
Pseudoboleite	$Pb_{31}Cu_{24}Cl_{62}(OH)_{48}$	Lavrion District slag localities, Greece (Gelaude et al. 1996)	OK	Boleo, Baja California Sur, Mexico (type) (Lacroix 1895)
Serpierite	$Ca(Cu,Zn)_4(SO_4)_2(OH)_6·3H_2O$	Lavrion District slag localities, Greece (Schnorrer-Köhler et al. 1991)	?	
Wroewolfeite	$Cu_4SO_4(OH)_6·2H_2O$	Lechnerberg slag locality, Kaprun, Hohe Tauern, Salzburg, Austria (Kolitsch and Brandstätter 2009)	?	
Wülfingite	$Zn(OH)_2$	Richelsdorf slags, Hesse, Germany (Schmetzer et al. 1985)	OK	Milltown, near Ashover, Derbyshire, U.K. (Clark et al. 1988)
Zlatogorite	$CuNiSb_2$	Castleside Smelting Mill slag locality, County Durham, England (Braithwaite et al. 2006)	OK	Zolotaya Gora gold mine, middle Urals Russia (type) (Spiridonov et al. 1995)
		E. Minerals associated with mine fires (not coal mines)		
Butlerite	$Fe^{3+}SO_4(OH)·2H_2O$	United Verde mine, Yavapai County, Arizona (type) (Lausen 1928)	OK	Saghand, Yazd Province, Iran (type) (Bariand et al. 1977)
Minium	$Pb^{2+}_2Pb^{4+}O_4$	Broken Hill, NSW, Australia (Skinner and McBriar 1958)	OK	Many
Ransomite	$CuFe^{3+}_2(SO_4)_4·6H_2O$	United Verde mine, Yavapai County, Arizona (type) (Lausen 1928)	?	
Shannonite	$Pb_2O(CO_3)$	Bluttenberg, Sainte-Marie-aux-Mines, Alsace, France (Kolitsch 1997)	OK	Grand Reef mine, Graham County, Arizona (type) natural (Roberts et al. 1995)
Yavapaiite	$KFe^{3+}(SO_4)_2$	United Verde mine, Yavapai County, Arizona (type) (Hutton 1959)	OK	Grotta dell'Allume, Vulcano, Italy (Demartin et al. 2010)
		F. Minerals associated with coal mine dumps		
Koktaite	$(NH_4)_2Ca(SO_4)_2·H_2O$	Žeravice, South Moravian Region, Czech Republic (type) (Sekanina 1948)	OK	Alfredo Jahn cave in central Venezuela (Forti et al. 1998)
		G. Minerals associated with coal mine and dump fires; Sublimation from gas escape from coal fires		
Alum-(Na)	$NaAl(SO_4)_2·12H_2O$	Szoros-patak shaft, Bátonyterenye, Hungary (Szakáll et al. 1997)	OK	Sunset Crater, San Franciscan volcanic field, Coconino County, Arizona (Hanson et al. 2008)
Arsenolite	As_2O_3	Mole River mine, northern New South Wales, Australia in dump (Ashley and Lottermoser 1999)	OK	Torrecillas mine, Iquique Province, Chile (Kampf et al. 2016f)
Bararite	$(NH_4)_2SiF_6$	Bararee colliery, Jharia coal field, India (type) (Palache et al.1951)	OK	Mt. Vesuvius, Naples, Italy (Palache et al. 1951)
Barberiite	$(NH_4)_2BF_4$	Anna 1 coal mine dump, Alsdorf, Germany (Witzke et al. 2015)	OK	La Fossa crater, Vulcano Island, Aeolian Archipelago, Italy (type) (Garavelli and Vurro 1994)
Boussingaultite	$(NH_4)_2Mg(SO_4)_2·6H_2O$	Coal mines, Chelyabinsk, Russia (Chesnokov et al. 2008)	OK	Travale, Montieri, Grosseto, Tuscany, Italy (type) (Bechi 1864)
Cryptohalite	$(NH_4)_2SiF_6$	Libosín, Kladno, Czech Republic (Zacek et al. 1995)	OK	Mt. Vesuvius, Naples, Italy (type) (Scacchi 1873; Palache et al. 1951)
Dmisteinbergite	$CaAl_2Si_2O_8$	Coal mine No. 45, Kopeisk, Russia (type) (Chesnokov et al. 2008)	OK	Gole Larghe Fault, Italian Alps (Nestola et al. 2010)
Dypingite	$Mg_5(CO_3)_4(OH)_2·5H_2O$	Coal mines No. 44, 45, Kopeisk, Russia (Chesnokov et al. 2008)	OK	Vestfold Hills, East Antarctica (Gore et al. 1996)
Efremovite	$(NH_4)_2Mg_2(SO_4)_3$	Coal mine No. 43, Kopeisk, Russia (type) (Chesnokov et al. 2008)	OK	Ravat Village, Tajikistan (Belakovskiy and Moskalev 1988; Nasdala and Pekov 1993; Belakovskiy 1998)
Esseneite	$CaFe^{3+}AlSiO_6$	Coal mines, Chelyabinsk, Russia (Chesnokov et al. 2008)	OK	Durham Ranch, Campbell County, Wyoming (type) (Cosca and Peacor 1987)
Fluorellestadite	$Ca_5(SiO_4)_{1.5}(SO_4)_{1.5}F$	Coal mine No. 44, Kopeisk, Russia (type) (Chesnokov et al. 2008)	OK	Jabel Harmun, Judean Mountains, Palestinian Automony (Galuskina et al. 2014)
Godovikovite	$(NH_4)Al(SO_4)_2$	Coal mines, Chelyabinsk, Russia (type) (Chesnokov et al. 2008)	OK	La Fossa crater, Vulcano, Italy (Campostrini et al. 2010)
Gwihabaite	$(NH_4)NO_3$	Kukhi-Malik, central Tajikistan (Belakovskiy and Moskalev 1988)	OK	Gcwihaba Cave, Kalahari basin, Botswana (type) (Martini 1996)

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TABLE 1b.—*CONTINUED*

Name (Localities)	Formula	Locality for anthropogenic mineral (reference)	Natural	Locality for natural mineral (reference)
Letovocite	$(NH_4)_3H(SO_4)_2$	Písečná, Letovice, Czech Republic (type) (Sekanina 1932)	OK	The Geysers, Sonoma County, California (Pemberton 1983, p. 279)
Mascagnite	$(NH_4)_2SO_4$	Coal mines, Chelyabinsk, Russia (Chesnokov et al. 2008)	OK	Travale, Montieri, Grosseto, Tuscany, Italy (type) (Mascagni 1779; Karsten 1800)
Mikasaite	$Fe^{3+}_2(SO_4)_3$	Ikushunbetsu, Mikasa City, Japan (type) (Miura et al. 1994; Shimobayashi et al. 2011)	?	
Millosevichite	$Al_2(SO_4)_3$	Lichtenberg Absetzer dump, Ronneburg, Gera, Thuringia, Germany (Witzke and Rüger 1998)	OK	Grotta dell'Allume, Vulcano, Italy (type) (Panichi 1913)
Mohrite	$(NH_4)_2Fe^{2+}(SO_4)_2 \cdot 6H_2O$	Coal mines 4/6 and 23, Chelyabinsk, Russia (Chesnokov et al. 2008)	OK	Travale, Montieri, Grosseto, Tuscany, Italy (type) (Garavelli 1964)
Ravatite	$C_{14}H_{10}$	Carola mine, Saxony, Germany (Witzke 1995)	OK	Ravat Village, Tajikistan (type) (Nasdala and Pekov 1993)
Rorisite	CaClF	Coal mine No. 45, Kopeisk, Russia (type) (Chesnokov et al. 1990, 2008)	OK	Tyrnyauz Mo-W deposit, northern Caucasus, Russia (Kulikov et al. 1982)
Rostite	$AlSO_4(OH) \cdot 5H_2O$	Libušín, Kladno, Czech Republic (type) (Čech et al. 1979; Palache et al. 1951)	?	
Srebrodolskite	$Ca_2Fe^{3+}_2O_5$	Coal mine 44, Kopeisk, Chelyabinsk, Russia (type) (Chesnokov et al. 2008)	OK	Jabel Harmun, Judean Mountains, Palestinian Automony (Galuskina et al. 2014)
Tinnunculite	$C_5H_4N_4O_3 \cdot 2H_2O$	Coal mine 44, Kopeisk, Chelyabinsk, Russia (Chesnokov et al. 2008)	OK	Mt. Rasvumchorr, Khibiny Mountains, Kola Peninsula, Russia (type) (Pekov et al. 2016)
		H. Mine water precipitates		
Alpersite	$(Mg,Cu^{2+})SO_4 \cdot 7H_2O$	Big Mike mine, Pershing County, Nevada (Peterson et al. 2006)	OK	Outwash basin, Cerro Negro and Momotombo volcanoes, León Department, Nicaragua (Hynek et al. 2013)
Jôkokuite	$Mn^{2+}SO_4 \cdot 5H_2O$	Johkoku mine, Kaminokuni, Japan (type) (Nambu et al. 1978)	OK	"Vienna Woods" hydrothermal field, Manus Basin, Bismark Sea, Papua New Guinea (Steger 2015)
Jurbanite	$AlSO_4(OH) \cdot 5H_2O$	San Manuel orebody, Pinal County, Arizona (type) (Anthony and McLean 1976)	?	Identification queried: Alum Cave Bluff, Great Smoky Mountains National Park, Tennessee (Coskren and Lauf 2000)
Khademite	$AlSO_4F \cdot 5H_2O$	Lone Pine mine, Catron County, New Mexico (type) (Williams and Cesbron 1983)	OK	Saghand, Yazd Province, Iran (type) (Bariand et al. 1973, 1977)
Kobyashevite	$Cu_5(SO_4)_2(OH)_6 \cdot 4H_2O$	On calcite and hemimorphite at the Ojuela mine, Mapamí, Durango, Mexico (RRUFF sample R160001)	OK	Kapital'naya mine, Vishnevye Mountains, South Urals, Russia (type) (Pekov et al. 2013)
Nickelhexahydrite	$NiSO_4 \cdot 6H_2O$	Severnyy mine, Norilsk-I deposit, Russia (type) (Oleynikov et al. 1965)	?	
Phaunouxite	$Ca_3(AsO_4)_2 \cdot 11H_2O$	Gabe Gottes mine, Alsace, France (type) (Bari et al. 1982)	?	
Rauenthalite	$Ca_3(AsO_4)_2 \cdot 10H_2O$	Gabe Gottes mine, Alsace, France (type) (Pierrot 1964)	?	
Rossite	$Ca(VO_3)_2 \cdot 4H_2O$	Blue Cap mine, San Juan County, Utah (Kampf and Steele 2008a)	?	
Sainfeldite	$Ca_5(AsO_4)_2(AsO_3OH)_2 \cdot 4H_2O$	Gabe Gottes mine, Alsace, France (type) (Pierrot 1964)	?	
Wilcoxite	$MgAl(SO_4)_2F \cdot 18H_2O$	Lone Pine mine, Catron County, New Mexico (type) (Williams and Cesbron 1983)	?	
		I. Mine timber alteration		
Devilline	$CaCu_4(SO_4)_2(OH)_6 \cdot 3H_2O$	Uspensky mine, Kazakhstan "herrengrundite" (Chukhrov and Senderova 1939; Palache et al. 1951)	?	372 localities (mindat)
Pentahydrite	$MgSO_4 \cdot 5H_2O$	Comstock Lode, Storey County, Nevada (Milton and Johnston 1938; Palache et al. 1951)	OK	Senegal; Argentina ILL
		J. Other "post-mine" minerals or context undefined		
Metarossite	$CaV^{5+}_2O_6 \cdot 2H_2O$	Bull Pen Canyon, San Miguel County, Colorado (type) (Foshag and Hess 1927)	?	
Monteponite	CdO	Monte Poni, Sardinia, Italy (type) (Pagano and Wilson 2014)	OK	Mottled Zone, Levant, Jordan (Khoury et al. 2016)
Rabbittite	$Ca_3Mg_3(UO_2)_2(CO_3)_6(OH)_4 \cdot 18H_2O$	Lucky Strike mine No. 2, Emery County, Utah (type) (Thompson et al. 1955)	?	
Rhomboclase	$(H_3O)Fe^{3+}(SO_4)_2 \cdot 3H_2O$	Smolnik, Košice Region, Slovakia (type); looks anthropogenic (Krenner 1928)	?	
Szomolnokite	$Fe^{2+}(SO_4)_2 \cdot H_2O$	Smolnik, Košice Region, Slovakia (type); looks anthropogenic (Krenner 1928)	OK	Saghand, Yazd Province, Iran (type) (Bariand et al. 1977)
Tschermigite	$(NH_4)Al(SO_4)_2 \cdot 12H_2O$	Čermnıky (Tschermig), Kaden, Czech Republic (type) (Palache et al. 1951; Parafiniuk and Kruszewski 2009)	OK	The Geysers, Sonoma County, California (Pemberton 1983)
Wupatkiite	$CoAl_2(SO_4)_4 \cdot 22H_2O$	Cameron, Coconino County, Arizona (type) (Williams and Cesbron 1995)	?	

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Table 1b.—*Continued*

Name (Localities)	Formula	Locality for anthropogenic mineral (reference)	Natural	Locality for natural mineral (reference)
II. Minerals associated with archeological artifacts				
		A. Alteration of lead artifacts		
Barstowite	$Pb_4CO_3Cl_6 \cdot H_2O$	Late-Hellenistic shipwreck, Mahdia, Tunisia (Kutzke et al. 1997)	OK	Bounds Cliff, Cornwall, England (type) (Stanley et al. 1991)
Cotunnite	$PbCl_2$	Late-Hellenistic shipwreck, Mahdia, Tunisia (Kutzke et al. 1997)	OK	Mt. Vesuvius, Naples, Italy (type) (Monticelli and Covelli 1825)
Phosgenite	$Pb_2CO_3Cl_2$	Late-Hellenistic shipwreck, Mahdia, Tunisia (Kutzke et al. 1997)	OK	Bounds Cliff, Cornwall, England (Stanley et al. 1991)
		B. Alteration of bronze artifacts		
Atacamite	$Cu_2Cl(OH)_3$	Egypt, on ancient bronze artifacts (Frondel and Gettens 1955; Gettens and Frondel 1955)	OK	Atacama Region, Chile (type) (Blumenbach 1803)
Chalconatronite	$Na_2Cu(CO_3)_2 \cdot 3H_2O$	Egypt, on ancient bronze artifacts (type) (Frondel and Gettens 1955; Gettens and Frondel 1955)	?	RRUFF ID: R070366 from Mont Saint-Hilaire, Rouville County, Québec, Canada: natural?
		C. Alteration of tin artifacts		
Romarchite	SnO	Boundary Falls, Winnipeg River, Ontario, Canada (Ramik et al. 2003)	OK	María Teresa mine, Huari, Oruro, Bolivia (Ramik et al. 2003)
Hydroromarchite	$Sn^{2+}_3O_2(OH)_2$	Boundary Falls, Winnipeg River, Ontario, Canada (Ramik et al. 2003)	OK	Cantiere Speranza (Corchia mine), Emilia-Romagna, Italy (Garuti and Zaccarini 2005)
		D. Prehistoric sacrificial burning sites		
Fayalite	Fe_2SiO_4	Goldbichl, Igls, Innsbruck, North Tyrol, Austria (Schneider et al. 2013)	OK	Fayal, Azores, Portugal (type) Gmelin (1840)
Forsterite	Mg_2SiO_4	Goldbichl, Igls, Innsbruck, North Tyrol, Austria (Schneider et al. 2013)	OK	Momte Somma, Vesuvius, Naples, Italy (type) (Levy 1825)
Stanfieldite	$Ca_4Mg_5(PO_4)_6$	Goldbichl, Igls, Innsbruck, North Tyrol, Austria (Schneider et al. 2013)	OK	Estherville, Iowa meteorite (type) (Fuchs 1967)
Whitlockite	$Ca_9Mg(PO_4)_6(PO_3OH)$	Ötz Valley, Northen Tyrol, Austria (Tropper et al. 2004)	OK	Palermo mine, Groton, New Hampshire (type) (Frondel 1941)
III. Miscellaneous human-mediated minerals				
		A. Minerals associated with geothermal pipe systems		
Larderellite	$NH_4B_5O_7(OH)_2 \cdot H_2O$	Larderello, Tuscany, Italy (type) (Bechi 1854; Ciriotti et al. 2009)	OK	La Fossa crater, Vulcano Island, Aeolian Archipelago, Italy (Campostrini et al. 2011)
Santite	$NH_4B_5O_7(OH)_2 \cdot H_2O$	Larderello, Tuscany, Italy (type) (Merlino and Santori 1970)	OK	La Fossa crater, Vulcano Island, Aeolian Archipelago, Italy (Campostrini et al. 2010)
Sassolite	$B(OH)_3$	Larderello, Tuscany, Italy (Merlino and Santori 1970)	OK	Sasso Pisano, Tuscany, Italy (type) (Karsten 1800; Ciriotti et al. 2009)
Sborgite	$NaB_5O_6(OH)_4 \cdot 3H_2O$	Larderello, Tuscany, Italy (type) (Cipriani 1957; Ciriotti et al. 2009)	OK	South Meridian claim, Furnace Creek, Death Valley, Inyo County, California (Erd et al. 1979)
		B.Mineral associated with alteration of pine railroad tie		
Arcanite	K_2SO_4	Santa Ana Tin mine, Orange County, California (type) (Frondel 1950; Eakle 1908)	OK	Sar Pohl diapir, Southern Iran (Talbot et al. 2009)
		C. Mineral formed by alteration of stored drill core		
Nickelbischofite	$NiCl_2 \cdot 6H_2O$	Dumont Intrusion, Amos, Québec, Canada (type) (Crook and Jambor 1979; Peacor et al. 1982)	OK	Mt. Shirane, Gunma Prefecture, Japan (Shima 1957)

Note: All listed minerals were approved by the IMA CNMNC.

activities (Table 1a), or as inadvertent human-mediated phases in some cases, but as natural phases (or phases suspected to occur as such) in other cases (Table 1b). Compilation of Tables 1a and 1b began with reading the "Occurrence" information in the Handbook of Mineralogy (Anthony et al. 1990–2003), together with global searches of mineral databases, mainly mindat.org, for such key terms as "artifact," "coal," "mine dump," "museum," and "slag." However, inclusion of minerals in the tables and the description of their paragenetic circumstances are based on the cited literature (unless consulting the cited source proved impossible as indicated in the bibliography).

It should be noted that not all authors have clearly stated whether human mediation had a role in the formation of the mineral under consideration. For example, a mineral collected from the walls of a mine tunnel might be of primary origin and thus a legitimate species. However, some mine-wall minerals are of secondary origin, forming as alteration products only because of the unique temperature and humidity environments associated with the mine; such minerals are considered to be mediated by human activities. In reading the literature, we have relied on published evidence or interviews with mineral collectors familiar with the area to infer whether human mediation was involved. A handful of minerals have been reported from more than one of the categories considered in Table 1, but the minerals have been listed under only one category. Note that in Table 1a we do not include nano-scale mineral-like compounds produced through combustion, for example coal ash or fly ash minerals (e.g., National Research Council 2006).

Table 2 lists mineral-like phases that are produced intentionally through industrial/commerical chemical processes, either as polycrystalline b).

TABLE 2a. Selected mineral-like synthetic compounds: Phases produced by manufacture of polycrystalline building and other materials, including chemical formulas and mineral equivalent

Name	Formula	Mineral equivalent
	Brick	
mullite	$Al_{4+2x}Si_{2-2x}O_{10-x}$ (x~0.4)	mullite
hematite	Fe_2O_3	hematite
quartz	SiO_2	quartz
diopside	$CaMgSi_2O_6$	diopside
	Earthenware	
quartz	SiO_2	quartz
feldspar	$KAlSi_3O_8$	sanidine
	Gypsum plaster	
gypsum	$CaSO_4{\cdot}2H_2O$	gypsum
anhydrite	$CaSO_4$	anhydrite
	High-temperature concrete	
CA_2	$CaAl_2O_4$	krotite
	Hydraulic (i.e., "Portland") cement	
"alite" or "C_3S"	Ca_3SiO_5 [several polymorphs]	hatruite
"belite" or "C_2S"	Ca_2SiO_4 [several polymorphs]	larnite
tricalcium aluminate	$Ca_3Al_2O_6$	–
tetracalcium aluminoferrite	$Ca_2AlFe^{3+}O_5$	brownmillerite
portlandite	$Ca(OH)_2$	portlandite
hillebrandite	$Ca_2SiO_3(OH)_2$	hillebrandite
ettringite [in supersulfated cement]	$Ca_6Al_2(SO_4)_3(OH)_{12}{\cdot}26H_2O$	ettringite
	Lime plaster	
lime	CaO	lime
calcite	$CaCO_3$	calcite
	Porcelain	
mullite	$Al_{4+2x}Si_{2-2x}O_{10-x}$ (x~0.4)	mullite
cristobalite	SiO_2	cristobalite

Mineral-like phases produced inadvertently as a consequence of human activities

Table 1a lists under different paragenetic categories the names and chemical formulas of 91 IMA CNMNC-approved minerals that are known or suspected to form exclusively as byproducts of human activities, including species associated with post-mine alteration (e.g., metamunirite; Fig. 1a), weathering of ore dumps, mineralization on mine walls and timbers, and mine water precipitates. Additional phases were identified in the piping networks of hydrothermal systems, notably Larderello, Tuscany, Italy (Cipriani 1957; Cipriani and Vannuccini 1961; Ciriotti et al. 2009), as corrosion products on archeological artifacts (e.g., abhurite; Fig. 1b; Gelaude et al. 1996) or mining artifacts (e.g., simonkolleite; Fig. 1c), and in the alteration of specimens in museum collections (Van Tassel 1945).

Of special interest are minerals found associated with ancient lead-zinc mine and slag localities, including some possibly dating from the Bronze Age (Kaprun, Austria; Kolitsch and Brandstätter 2009), others from as far back as 300 AD, as in the Harz, Germany (van den Berg and von Loon 1990). The best known and most prolific slag localities are near the coast of Lavrion (also known as Laurion or Laurium), Attiki Prefecture, Greece (e.g., Lacroix 1896; Hanauer and Heinrich 1977; Gelaude et al. 1996; Kolitsch et al. 2014). These deposits have yielded more than a dozen hydrous chloride phases formed by interaction of slag with seawater, for example, fiedlerite (Fig. 1d) and nealite (Fig. 1e)—at least seven of which were first described at Lavrion (Palache et al. 1951; Kohlberger 1976). A unique category comprises a Fe-Ta intermetallic and two Ta-Nb carbides from Middle Ural placers, more likely the Nizhnii Tagil ultramafic massif (Pekov 1998). Pekov reviewed the puzzling and mysterious history of these compounds; our conclusion from discussion of Pekov (1998) is that a natural origin is most unlikely, and that possibly synthetic material had been deliberately sent to mineralogists for study.

Some of these human-mediated minerals, although no longer conforming to IMA CNMNC requirements for new species, were approved prior to the IMA CNMNC statements of 1995. Nickel and Grice (1998) decided that substances already accepted in the past are not to be automatically discredited as a result of the new rulings, as it was their intention to establish guidelines for the future.

The 117 minerals listed in Table 1b are representative of the diverse crystalline phases that occur both through human and natural processes; however, Table 1b is not comprehensive. For example, a total of 254 mineral-like compounds have been reported from coal mine dump fires in the Chelyabinsk coal basin (e.g., Kopeisk), southern Urals, Russia (Chesnokov et al. 2008; Sharygin 2015), of which 183 have naturally occurring analogs. A comparable diversity has been described in detail from the Anna I coal mine dump in Aachen region, Germany (Witzke et al. 2015). Moreover, many more species are known primarily through natural processes, but also occur as inadvertent byproducts of human activities. For example, calcite ($CaCO_3$), gypsum ($CaSO_4{\cdot}2H_2O$), and halite (NaCl) are phases that occur in the white efflorescence that commonly coats weathered concrete masonry units (i.e., "cinder blocks;" Wallach et al. 1995), whereas the green "verdigris" coating on copper metal may include atacamite and paratacamite [both $Cu_2(OH)_3Cl$], malachite [$Cu_2CO_3(OH)_2$], and various hydrous copper sulfates (Fitzgerald et al. 1998). The majority of phases reported in Table 1b are associated with mining, especially post-mine alteration of ore minerals. Several additional phases in Table 1b arise through the weathering of ancient metal artifacts, heating in prehistoric sacrificial burning sites, or alteration of specimens in museum collections. Thus, primarily human-mediated minerals may represent as many as 6% of the more than 5100 IMA approved mineral species.

However, we should note that several minerals listed in Tables 1a and 1b, which apparently do not conform to IMA CNMNC requirements for new species, were approved after the 1995 (and again in 1998) publication of guidelines. Such species were approved possibly owing to the difficulty in evaluating if a potential new mineral "owes its origin, at least in part, to human activities such as mining or quarrying. If such substances are formed purely as a result of the exposure of existing rock or minerals to the atmosphere or to the effects of groundwater, they can generally be accepted as minerals." A case in point is the occurrence at Mont Saint-Hilaire, Quebec of chalconatronite (Fig. 1f), which Andrew McDonald (personal communication) reports as found in interstices among the blocks of sodalite syenite xenoliths. If chalconatronite had formed during exposure by quarrying to subaerial weathering, then chalconatronite can be considered a bona fide mineral at Mont Saint-Hilaire by the IMA CNMNC criterion cited above. In other words, whether a compound is a valid mineral or not depends on how its origin is interpreted, introducing thereby another source of uncertainty in the evaluation of new mineral proposals. This situation allows

Table 2b. Selected synthetic/refined crystals and crystalline materials, including uses, chemical formulas, and mineral equivalent and mineral structure type (if applicable)

Name	Formula [dopant]	Mineral equivalent[a]	Structure type[a]
Abrasives			
diamond	C	diamond	diamond
boron carbide	B_4C	unnamed	B_4C
boron nitride	c-BN	qingsongite	sphalerite
boron nitride	w-BN	–	wurtzite
tungsten carbide	WC	qusongite	NaCl
alumina	Al_2O_3	corundum	corundum
Batteries			
lead-acid battery	Pb	lead	lead
	PbO_2	plattnerite	rutile
	$PbSO_4$	anglesite	barite
NiCad batteries	NiO(OH)	–	β-NiO(OH)
	$Ni(OH)_2$	theophrastite	brucite
	$Cd(OH)_2$	–	brucite
	Cd	cadmium	zinc
lithium ion batteries	$LiCoO_2$	–	$LiCoO_2$
	CoO	–	periclase
	CoO_2	–	CdI_2
NiMH battery	$Ni(OH)_2$	theophrastite	brucite
	NiO(OH)	–	β-NiO(OH)
	REE hydrides	–	fluorite
Ferroelectric/piezoelectric crystals			
barium titanate	$BaTiO_3$	barioperovskite	perovskite
lithium niobate	$LiNbO_3$	–	perovskite
lithium tantalate	$LiTaO_3$	–	perovskite
PZT	$Pb(Zr_xTi_{1-x})O_3$	–	perovskite
Gemstones			
diamond	C	diamond	diamond
moissanite	SiC	moissanite	wurtzite
cubic zirconia	ZrO_2	baddelyite	baddelyite
rutile	TiO_2	rutile	rutile
GGG	$Gd_3Ga_5O_{12}$	–	garnet
bismuth antimonite	$Bi^{3+}Sb^{5+}O_4$	kyawthuite	clinocervantite
Infrared crystals			
barium fluoride	BaF_2	frankdicksonite	fluorite
cadmium selenide	CdSe	cadmoselite	wurtzite
cadmium sulfide	CdS	greenockite	wurtzite
cadmium telluride	CdTe	–	wurtzite
calcium fluoride	CaF_2	fluorite	fluorite
lithium fluoride	LiF	gricite	halite
magnesium fluoride	MgF_2	sellaite	rutile
zinc selenide	ZnSe	stilleite	sphalerite
zinc sulfide	ZnS	wurtzite	wurtzite
zinc telluride	ZnTe	–	sphalerite
Laser crystals			
ruby	Al_2O_3 [Cr]	corundum	corundum
sapphire	Al_2O_3 [Ti]	corundum	corundum
YAG	$Y_3Al_5O_{12}$ [Nd]	–	garnet
alexandrite	$BeAl_2O_4$	chrysoberyl	olivine
yttrium vanadate	YVO_4 [Nd]	–	zircon
Magnets (permanent)			
ferrite	Fe_3O_4	magnetite	spinel
	$ZnFe_2O_4$	franklinite	spinel
	$CoFe_2O_4$	–	spinel
	$BaFe_{12}O_{19}$	barioferrite	plumboferrite
	$SrFe_{12}O_{19}$	–	plumboferrite
REE	$SmCo_5$	–	$CaCu_5$
	Sm_2Co_{17}	–	Th_2Ni_{17}
Neodymium magnets	$Nd_2Fe_{14}B$	–	$Nd_2Fe_{14}B$
Metals/Alloys			
aluminum	Al	aluminum	ccp-Cu
beryllium	Be	–	hcp-Mg
titanium	Ti	titanium	hcp-Mg
tungsten	W	tungsten	bcc-W
molybdenum	Mo	–	bcc-W
gold	Au	gold	ccp-Cu
silver	Ag	silver	ccp-Cu
platinum	Pt	platinum	ccp-Cu
steel	Fe, C [Mo/Mn/Co/Ni/Cr/Al]	–	–
bronze	Cu-Sn	–	–
brass	Cu-Zn	–	–
pewter	Sn-(Cu,Sb,Bi)	–	–
Optics applications (accousto-optic, non-linear optic, ElectroOptic)			
barium borate	$Ba(BO_2)_2$	–	β-$Ba(BO_2)_2$
lithium borate	LiB_3O_5	–	LiB_3O_5
bismuth germinate	$Bi_4Ge_3O_{12}$	–	$Bi_4Si_3O_{12}$
bismuth silicate	$Bi_{12}SiO_{20}$	sillénite	sillénite
lead molybdate	$PbMO_4$	wulfenite	scheelite
tellurium oxide	TeO_2	tellurite	tennantite
rutile	TiO_2	rutile	rutile
calcite	$CaCO_3$	calcite	calcite
magnesium aluminate	$MgAl_2O_4$	spinel	spinel
Phosphors			
BAM	~$BaMgAl_{10}O_{17}$ [Eu/Mn]	–	$BaMgAl_{10}O_{17}$
BSP	$BaSi_2O_5$ [Pb]	sanbornite	sanbornite
CAM	$LaMgAl_{11}O_{19}$ [Ce]	–	$LaMgAl_{11}O_{19}$
calcium tungstate	$CaWO_4$	scheelite	scheelite
cadmium tungstate	$CdWO_4$	–	wolframite
magnesium tungstate	$MgWO_4$	huanzalaite	wolframite
SAC	$SrAl_{12}O_{19}$ [Ce]	–	$CaAl_{12}O_{19}$
SMS	$Sr_2MgSi_2O_7$ [Pb]	–	mellilite
strontium aluminate	$SrAl_2O_4$ [Eu/Dy]	–	$SrAl_2O_4$
YAG	$Y_3Al_5O_{12}$ [Ce/Tb]	–	garnet
yttrium oxide	Y_2O_3 [Eu]	–	bixbyite
yttrium oxide sulfide	Y_2O_2S [Eu/Tb]	–	La_2O_3
yttrium silicate	Y_2SiO_5 [Ce]	–	Gd_2SiO_5
zinc oxide	ZnO [Ga]	zincite	wurtzite
zinc sulfide	ZnS [Ag/Mn]	wurtzite	wurtzite
zinc silicate	Zn_2SiO_4 [Mn]	willemite	phenakite
zinc phosphate	$Zn_3(PO_4)_2$ [Mn]	–	$Zn_3(PO_4)_2$
Scintillation crystals			
sodium iodide	NaI [Tl]	–	halite
cesium iodide	CsI [Tl]	–	CsCl
calcium fluoride	CaF_2 [Eu]	fluorite	fluorite
YIG	$Y_3Fe_5O_{12}$	–	garnet
yttrium aluminate	$YAlO_3$	–	perovskite
Semiconductors			
germanium	Ge	–	diamond
silicon	Si [Al,P]	silicon	silicon
gallium-aluminum arsenide	$Al_xGa_{1-x}As$	–	sphalerite
gallium antimonide	GaSb	–	sphalerite
gallium phosphide	GaP	–	sphalerite
indium phosphide	InP	–	sphalerite
tin sulfide	SnS	herzenbergite	GeS

[a] Dash (–) indicates no mineral equivalent.

for approval of some new minerals that may not have an entirely natural origin (Tables 1a and 1b).

Synthetic mineral-like compounds

Modern technology and commerce depends on myriad synthetic inorganic compounds (e.g., Warner 2011; Schubert and Hüsing 2012; Rao and Biswas 2015). Accordingly, Table 2 lists a wide variety of mineral-like synthetic phases that are intentional byproducts of human commercial activities. These varied compounds differ from those in Table 1 in that they arise from directed chemical reactions—industrial processes undertaken with the intention of producing crystalline materials with useful properties. In this regard, the relationship of phases in Tables 1 to those in Table 2 is in some ways analogous to the division of biominerals into “indirect” vs. “directed” compounds (Mann 2001; Perry et al. 2007). Indirect biominerals (what Perry et al.

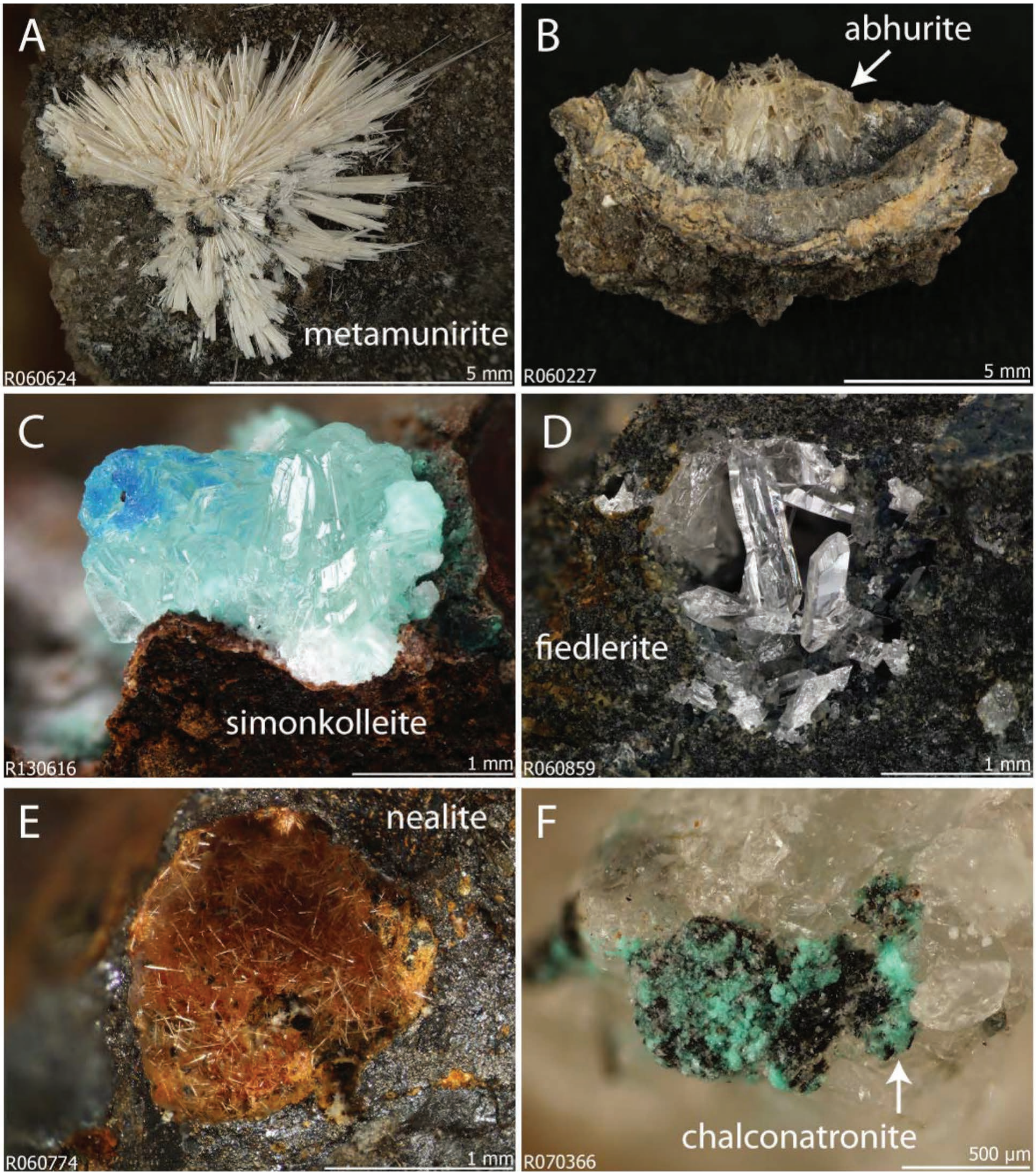

FIGURE 1. Anthropogenic minerals from the RRUFF collection (Downs 2006). (**a**) Tan-colored divergent radial spray of bladed crystals of metamunirite ($NaV^{5+}O_3$), Big Gypsum Valley, San Miguel County, Colorado. (**b**) Aggregate of tan-colored platy crystals of abhurite [$Sn^{2+}_{21}O_6(OH)_{14}Cl_{16}$] from the wreck of the SS Cheerful, 14 miles NNW of St. Ives, Cornwall, England. (**c**) Colorless hexagonal tabular crystals of simonkolleite [$Zn_5(OH)_8Cl_2 \cdot H_2O$] associated with blue platy crystals of composition $CuZnCl(OH)_3$ on a copper mining artifact, Rowley mine, Maricopa County, Arizona. (**d**) Colorless prismatic crystals of fiedlerite [$Pb_3Cl_4F(OH) \cdot H_2O$] associated with phosgenite, polytype 1*A*, from a Lavrion slag locality, Greece. (**e**) Reddish brown acicular crystals of nealite [$Pb_4Fe(AsO_3)_2Cl_4 \cdot 2H_2O$] coating a vug, from an Oxygon slag locality, Lavrion, Greece. (**f**) Blue fine-grained crust of chalconatronite [$Na_2Cu(CO_3)_2 \cdot 3H_2O$], Mont Saint-Hilaire, Quebec, Canada. (Color online.)

2007 refer to as “organominerals”) include a host of microbially precipitated ore minerals and other phases (e.g., Southam and Saunders 2005; Yang et al. 2011) that arise through local biologically mediated changes in chemical environments. By contrast, directed biomineralization leads to the formation of functional hard parts, including shells, teeth, and bones (Weiner and Addadi 1997; Skinner and Jahren 2003).

Table 2, similarly, lists “functional” phases that are manufactured through directed processes. Fine-grained crystalline constituents of cement, porcelain, bricks, and other manufactured polycrystalline materials appear in Table 2a. Several of these products arise from the high-temperature firing of clay-bearing starting materials. Thus principal constituents of porcelain ("china," typically fired at $1200 < T < 1400$ °C) are mullite plus cristobalite; those of "earthenware" ($1000 < T < 1150$ °C) include quartz and feldspar; whereas fired bricks ($900 < T < 1000$ °C) incorporate quartz, mullite, and diopside, as well as hematite in red bricks (Chaudhuri and Sarkar 1995; Cultrone et al. 2005).

The mineral-like compounds in hydraulic cements (including portland cement) have received special attention for their complexity, diversity, and evolution as cement cures (e.g., Taylor 1997). The four principal "mineral" components of cement are "alite" or "C_3S" (ideally Ca_3SiO_5, although invariably with minor Mg, Na, Fe, Al, and P), "belite" or "C_2S" (ideally Ca_2SiO_4, but commonly with many impurities, including Na, Mg, K, Fe, Al, and S), tricalcium aluminate or "C_3A" ($Ca_3Al_2O_6$), and tetracalcium aluminoferrite or "C_4AF" (ideally $Ca_2AlFe^{3+}O_5$, the mineral brownmillerite, although commonly with significant Mg and Ti, as well). The calcium aluminate, $CaAl_2O_4$, or CA_2, although the main constituent in cement valued for high sulfate resistance (e.g., Kahlenberg 2001), is extremely rare in nature—the mineral krotite has to date been reported from a single microscopic Ca-,Al-rich inclusion (CAI) in the Northwest Africa (NWA) 1934 meteorite (Ma et al. 2011). Complexity arises from multiple structure types for anhydrous C_3S and C_2S, as well as numerous hydrated variants of the four principal phases—compounds that are critical to the curing and strength of cement. Portlandite [$Ca(OH)_2$] also constitutes an important mineral-like phase in cured concrete. Note that, with the exception of the contact metamorphic minerals hatrurite (natural high-temperature C_3S), larnite (β-Ca_2SiO_4), calcio-olivine (γ-Ca_2SiO_4), brownmillerite (natural C_4AF), and krotite, most of these mineral-like phases have not been found in nature. Calcio-olivine (γ-Ca_2SiO_4) is a polymorph of C_2S, but it does not hydrate and is therefore avoided in cement manufacturing.

Table 2b lists examples of synthetic crystals and crystalline phases employed in various technological and commercial applications. Some of these phases are well known as minerals, including most synthetic gemstones and abrasives (in both cases including diamond and corundum), which are designed to mimic the physical behaviors of natural crystals. By contrast, there are exceedingly rare minerals such as an unnamed B_4C (Kaminsky et al. 2016); qingsongite (BN), which is the natural analog of the widely used abrasive "Borazon" (Dobrzhinetskaya et al. 2014); and kyawthuite, $Bi^{3+}Sb^{5+}O_4$, which is only known in nature from a single faceted gemstone from Mogok, Myanmar, whereas the synthetic form has been extensively employed in ceramics and as a catalyst (Kampf et al. 2017). However, many phases in Table 2b, notably those designed for use in magnets, batteries, phosphors, and varied electronic and optical applications, are not yet known to occur in nature owing to their controlled compositions incorporating one or more rare elements. Large-scale production of metals and alloys provides another distinctive class of crystalline phases that characterize human civilization.

Of special importance are numerous synthetic crystals that incorporate one or more dopant elements. Common examples include Al- and P-doped silicon semiconductors; Mn-doped zinc silicate and phosphate phosphors; and varied laser crystals, including ruby (Cr-doped corundum) and Nd-doped yttrium aluminum garnet, or "YAG."

IMPLICATIONS: MINERALOGICAL MARKERS OF THE ANTHROPOCENE EPOCH

At least three consequences of human activities have affected the diversity and distribution of minerals and mineral-like compounds in ways that might be reflected in the worldwide stratigraphic record. The most obvious influence—the one examined by Zalasiewicz et al. (2013) and in Table 2—is the widespread occurrence of synthetic mineral-like materials. These diverse human products are likely to survive far longer than most of the indirect human-mediated minerals of Table 1.

Prior to human activities, the most significant "punctuation event" in the diversity of crystalline compounds on Earth followed the Great Oxidation Event. Hazen et al. (2008) estimated that as many as two-thirds of Earth's more than 5000 mineral species arose as a consequence of the biologically mediated rise of oxygen at ~2.4 to 2.2 Ga. By comparison, the production of the more than 180 000 inorganic crystalline compounds (as tabulated in the Inorganic Crystal Structure Database; http://icsd.fiz-karlsruhe.de) reflects a far more extensive and rapid punctuation event. Human ingenuity has led to a host of crystalline compounds that never before existed in the solar system, and perhaps in the universe. Thus, from a materials perspective (and in contrast to Earth's vulnerable biodiversity), the Anthropocene Epoch is an era of unparalleled inorganic compound diversification.

Perhaps the most pervasive, persistent, and unambiguous anthropogenic mineral-like phases are those employed in constructing buildings and roads, notably reinforced concrete, a composite material of steel rebar embedded in concrete. Resilient polycrystalline materials, including bricks, earthenware, porcelain, and cement, along with various glass, serve as additional obvious Anthropocene marker "lithologies." Another anthropogenic impact is transport over long distances of building stone from its original location, often cut into rectangular blocks and sculptural forms, to new sites such as roads, bridges, monuments, kitchen counters, and the infrastructure of cities—in effect, a redistribution of "anthropogenic xenoliths" rivaling natural redistribution by glaciers. Examples for preservation of such materials under geological conditions are the Roman cities Pompeii and Herculaneum buried under volcanic ash in AD 79 and the ancient city of Alexandria buried during subsidence under the Mediterranean Sea.

Robust crystalline materials such as silicon "chips" for semiconductors, carbide grits for abrasives, YAG crystals for lasers, and various specialty metals and alloys for magnets, machine parts, and tools are less volumetrically significant and more localized, but equally distinctive as anthropogenic phases. As with many paleontological sites (limestone reefs or Lagerstätten, for example), many of these synthetic materials will be preserved in lens-like concentrations, representing collapsed buildings, parking lots, solid waste sites, or other localized environments.

A second human influence on the distribution of Earth's near-surface minerals relates to large-scale movements of rocks and sediments—sites where large volumes of rocks and minerals have been removed. Mining operations have stripped the near-surface environment of ores and fossil fuels, leaving large open pits, tunnel complexes, and, in the case of strip mining, sheared off mountaintops. In these instances, the absence of mineral concentrations provides "index fossils" of human commerce. Roadcuts, tunnels, and embankments represent further distinctively human modifications of the landscape—what Zalasiewicz et al. (2014) have termed "human bioturbation."

Finally, humans have become relentlessly efficient in redistributing natural minerals across the globe. Diamonds, rubies, emeralds, sapphires, and a host of semi-precious stones, accompanied by concentrations of gold, silver, and platinum, are found in shops and households in every corner of the globe. And, perhaps most distinctive of all, hundreds of thousands of individuals around the world have amassed collections of fine mineral specimens—accumulations that juxtapose mineral species that would not occur naturally in combination. From modest beginner sets of more common minerals to the world's greatest museums, these collections, if buried in the stratigraphic record and subsequently unearthed in the distant future, would reveal unambiguously the passion of our species for the beauty and wonder of the mineral kingdom.

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