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A Mineralogy for the Anthropocene

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This essay is a follow-up on « La signature stratigraphique de l'Anthropocène », which is also available on HAL- Archives ouvertes.

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Warning. This paper is written to be read by both specialists and a wider audience. However, it contains many mineral names. While these may resonate in the minds of mineralogists or collectors, they may not be as meaningful to less discerning readers. Such readers should not be scared, for they may find excellent encyclopaedic records on the web, including chemical composition, crystallographic properties and description of each of these species. This is why we have decided not to include further information in this paper.

Acknowledgements. I would like to thank the mineralogists with whom I have had the opportunity to maintain fruitful exchanges for a long time: my pupil Hubert Bari, Éric Asselborn, Cédric Lheur, François Farges. And I would like to honour the memories of René Weil (1901-1983), my master in descriptive mineralogy, and of Jacques Geffroy (1918-1993), pupil of Alfred Lacroix, my master in metallogeny.

Abstract

Many mineral species, objects of research or appreciated by collectors, owe their existence to the action of human societies. Through their activities, humans modify the Earth's surface—the stratigraphic entities of the Anthropocene—or pierce its interior, creating physico-chemical imbalances in ecosystems of widely varying scales. Once Man turns away from his works, Nature acts alone and produces minerals. Their belonging to the catalogue of recognised mineral species is the subject of lively debate among specialists. We shall try and provide further arguments to this debate. Based on the analysis of case studies—an old mine gallery, a coal mine slag heap, foundry slags, buried archaeological metals—this paper attempts to show both the richness of a true

mineralogy of the Anthropocene—as a scientific approach—and its limits in the direction of the "artificial" on one side, and the infinitely small on the other.

1. Introduction: neof ormation minerals in ancient mining galleries

"These stalactites are formed as a kind of vegetation... by branching out as they spread... it is indeed the crystallization of the whole cave from end to end... it is in the deepest parts of these mountains that most of these concretions are formed; proof of this is to be found in the ancient galleries, which have been plugged up for a long time and were filled with stalactites once uncorked".¹

Man has pierced the earth's crust with millions of kilometres of pipes, galleries, shafts and stopes. In these underground places, the circulation of water has given rise to the crystallization of mineral species. This is the case with carbonate concretions in the form of coral-like *aragonite*, which sometimes literally clutter up old works [Fig. 1]. These neof ormations are faithful replicas of those resulting from the work of nature in karst environments, in which the two polymorphs of calcium carbonate are found. *Aragonite* seems to enjoy the presence of iron carbonate, *i.e.* on metal deposits, hence the name *Eisenblüte*—iron flower—that was once given to it, as in the iron mines of Styria [Fig. 2]. This category of neof ormations also includes *halite* stalactites in salt mines [Fig. 3], as well as those of *epsomite* (a magnesium sulfate), and different kinds of salts. But also many other species, many of which contain metal cations, such as iron or copper sulfates in massive sulphides deposits [Fig. 4]. In the galleries of Banská Bystrica (Neusohl) in Slovakia—formerly Lower Hungary—these salts are dissolved in underground water; on a study trip to the site, in 1728, Montesquieu was impressed by the spectacle of the cementation of copper from such solutions.²

A textbook case is offered by the metal-bearing veins of the famous bismuth-cobalt-nickel-arsenic ("BiCoNi") paragenesis³, widespread in Central Europe. Arsenic is common in its native state in these mineral associations. Exposed to seepage water runoff, it enters into solution, charging the water with arsenic acid. The latter reacts against carbonate gangues to give rise to calcium arsenates, or which host other cations. This is notably the case at Sainte-Marie-aux-Mines (France), whose neof ormed mineral species caused a veritable effervescence at the end of the 1970s in the mineralogy laboratory of the University of Strasbourg [Fig. 5]. Several "first world descriptions" were thus conducted there, giving rise to new species (in alphabetical order): *ferrarisite*, *fluckite* [fig. 6], *giftgrubeite* (described in 2016), *mcnearite*, *phaunouxite*, *rauenthalite* [fig. 7], *sainfeldite*, *smamite* (described in 2019), *weilite*. These species are dedicated to scholars or places, namely (in the same order): Giovanni Ferraris, Pierre Fluck, the Giftgrube mine, Elisabeth McNear, the Vallon de Phaunoux (French designation of Rauenthal), the Vallon du Rauenthal (German designation of Phaunoux), Paul Sainfeld, Sainte-Marie-aux-Mines, René Weil⁴.

¹ MONNET A.-G. *Septième voyage*, édité et commenté par P. Fluck, « Voyages, aventures minéralogiques au siècle des Lumières en alsace, Lorraine et Franche-Comté », Éd. du Patrimoine Minier et Do Bentzinger, 2012, p. 367-368.

² BERTRAND G., BOTS H., BRIZAY F., COURTNEY C.-P., COUTIRIER-HEINRICH C., FLUCK P., MASCOLI-VALLET L., PAPOFF G., POMMIER H., RETAT P., *Montesquieu, Œuvres complètes*, tome 10 *Mes voyages*, sous la direction de Jean Ehrard, Lyon - Paris, ENS Éditions/Classiques Garnier, 2012

³ You should understand *paragenesis* as a mineral association.

⁴ PIERROT R., Contribution à la minéralogie des arsénates calciques et calcomagnésiens naturels, *Bull. Soc. Franç. Minéral. Cristallogr.*, 87, 1964, p. 169-211. BARI H., Minéralogie des filons du Neuenberg à Sainte-Marie-aux-Mines

There is a concept which has been adopted by our German neighbours for several decades, while the French have proved more reserved in making use of it: that of **geotope**. A geotope is a place in the geosphere, generally on its surface, which can be considered remarkable for the quality of the information it provides, or for its perceived heritage value: for instance, a quarry dug in a *stratotype*, or an outcrop of organ pipes [Fig. 8]. The sections of old galleries scattered with what poets describe as 'underground flora' are authentic geotopes.

It should be noted that, in absolute terms, such species can form in the natural cavities of veins—whose interiors are frequently *geodic*—as long as they can be drained by meteoric waters. However, most crystallizations owe their existence to the action of Man: the miners, digging the underground environment, have both made possible or accelerated the circulation of water, and offered the supports and voids thus prepared for crystals to grow in. Without, of course, any intention to create a specific mineral ecosystem. We are indeed in the presence of natural processes occurring "blindly" in previously modified environments—one could almost say "prepared" by Man.

But neoformed minerals are not limited to the cavities created by mining operations. In 2006, I had the opportunity to study, with the team of the Egyptologist Claude Traunecker, tomb 33 of the Necropolis of Thebes (Padiamenopé); the walls of the ducts were found to be studded with a veritable flora of fine saline crystallisations [Fig. 9]. Having no analytical means at my disposal, and being unable to take even a single needle from these neoformations, I had to resort to attempts at "organoleptic" determinations, which remain uncertain. I thus described encrustations or efflorescence of Na_2SO_4 *thenardite*, stalactites of $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ *epsomite*, pustules or dark crusts of KNO_3 *saltpetre*.⁵

If one assimilates these neoformations to concretions, *i.e.* minerals forming on a substrate, in a trap-structure such as an artificial cavity, it is tempting to add other types of crystallizations. A book published by Prüss publisher in Strasbourg, titled "Gart der Gesundheit" (Garden of Health), lists the animals, plants and stones in an encyclopaedic review presented in alphabetical order⁶, in a common language (German). We have been working on the 1509 edition. At that time, and for a long time to come, no distinctions were made between rocks and minerals. The world of stones ("von den Steinen") is a catalogue with 144 entries. We shall come back to this later. Among them is a stone called *tartarus* or *Weinstein* [fig. 10]: modern chemistry tells us that it is *potassium bitartrate*, which is deposited in crystalline crusts in wine barrels. Isn't it remarkable that in the term *Weinstein*, the word "stone" appears? A product of organic composition, just like a number of natural mineral species.

Anthropogenic minerals in fire-drilled work. The small Bluttonberg area is an extension of the polymetallic district of Ste-Marie-aux-Mines (France). In its dumps U. Kolitsch⁷ collected ruby colored samples, in which he described species which he interpreted as newly formed in the old

(Haut-Rhin), *Pierres et Terre* 23-24, 1982, p. 3-143; MEISSER N., PLÁŠIL J., BRUNSPERGER Th., LHEUR C., ŠKODA R., Giftgrubeite, $\text{CaMn}_2\text{Ca}_2(\text{AsO}_4)_2(\text{ASO}_3\text{OH})_2 \cdot 4\text{H}_2\text{O}$, a new member of the hureaulite group from Sainte-Marie-aux-Mines, Haut Rhin Departement, Vosges, France, *Journal of Geosciences* (Czech Geological Society), 64, 2019, p. 73-80 (en ligne <http://www.jgeosci.org/detail/jgeosci.276>).

⁵ FLUCK P., Tomb 33 of the Necropolis of Thebes. Geological Expertise. 2006 (limited diffusion)

⁶ Johannes DE CUBA, *Gart der Gesundheit* ou *Ortus sanitatis*, published in Mainz in 1485, then in Strasbourg in 1487. On the section devoted to stones, see FLUCK P., Ressources minérales: explications scientifiques et savoir-faire technique de la Protohistoire à aujourd'hui, in *Les Ressources*, Colloque Institut Universitaire de France, Université de St-Etienne, 2011, p. 81-97.

⁷ *Der Aufschluss*, March-April 1997

workings under the effect of fire-blasting, probably followed by leaching: *hydrocerussite*, *shannonite* $\text{Pb}_2\text{O}(\text{CO}_3)$, *elyite* $\text{Pb}_4\text{Cu}(\text{SO}_4)\text{O}_2(\text{OH})_4 \cdot \text{H}_2\text{O}$, *litharge*, *tenorite*.

2. Minerals from burning coal mines

On May 21, 2018, the members of the *Mining Heritage Federation* surveyed the waste piles of the former coal mines of Lalaye, in central Alsace (France)⁸. The materials that make up these heaps of schist and debris are partly rubified, showing orange hues that result from cooking under the action of an internal fire. In the coal basins of Nord-Pas de Calais, Wallonia, Ruhr, in Comentry, Ronchamp, Alès or Aveyron, the large tailings "burn inside": their walls are hot in places and such combustions can last for several decades [fig. 11]⁹. The coal shale is in fact loaded with pyrite (an iron sulfide), which under the action of percolating water decomposes into sulfate, a reaction releasing heat¹⁰, which is further activated by the volatile fraction released by the shale rich in organic matter. The various metal ions are thus carried by the hot gases circulating in the cracks or joints of these slag heaps, before precipitating in different forms near the surface, where fumaroles spark up in the form of small volcanos: *salammoniac*, *sulfur* and sulfur compounds, *alunogen*—an alumine sulfate—, potassium or ammonium *alums*, *epsomite*, *vivianite*, oxides and arsenic sulfides [fig. 12 and 13]¹¹...

So far we have been talking about the surface of the spoil heap. But let's see what goes on inside... where it's more difficult to access! This "hostile" environment can be brought to the surface by the economic exploitation of the materials that make up the fill. These excavations reveal rocks quite close to certain lava, composed of minerals such as *tridymite*—a form of high-temperature silica—, *osumilite*—a complex silicate—, *mullite*—an alumina silicate close to *sillimanite*—, or glass, all of which are minerals present in nature within volcanic formations¹². Almost all of these mineral species, both those on the surface and those in the heart of the heap, have their equivalent in nature.

Many collectors are fond of the above-mentioned fumarolite neoformations, offering crystals of good aesthetic quality. The most serious essays and books on mineralogy describe them most naturally in the world, such as Alfred Lacroix's *Minéralogie de la France (Mineralogy of France)*, and the historiography of the discipline reveals many publications on these species¹³.

This is a perfect class of neoformations that can be identified with Anthropocene Mineralogy. This challenge, however, is not unanimously accepted by the community of those curious about mineralogy (both researchers and collectors). One can be legitimately led to refuse to these formations the right to be included in the list of what nature produces, despite their being authentic mineral species, such as those that appear in all descriptive mineralogies. On behalf of the *International Mineralogical Association*, Nickel and Grice emphatically refute the designation

⁸ Mines exploited in the 18th and 19th centuries; FLUCK P., Le puits Mathis réouvert 26 ans après sa fouille, *Annuaire Soc. Hist. Val de Villé*, 2018, p. 168-178.

⁹ INERIS (Institut National de l'Environnement Industriel et des Risques) or other organisations have implemented *airborne thermography* operations, which produce a very accurate image of the temperature gradients on the surface of burning spoil heaps. In 2002, the twin spoil heaps of the Couriot shaft in Saint-Etienne (France) revealed a detailed mapping of their surface heat by this means.

¹⁰ Sometimes, forest fires can spread to the materials in the spoil heaps.

¹¹ As well as metal sulfides, such as *stibine*, *bismuthinite*, *galena*... or sulfates such as *vivianite*.

¹² VIDAL M., MIRIBEL M., DELORME H., BEAL M., Les terrils, vestiges du bassin houiller de la Loire, *Revue des Amis du Musée de la Mine de St-Etienne*, 55, déc. 2016.

¹³ MAYENÇON F., Sur quelques produits volatils des mines de houille incendiées, *C. R. Acad. Sci.* 86, 1878, p. 491-493. COLLET A., Notes minéralogiques, *Bull. Soc. Linnéenne Lyon*, 1946, p. 19-23.

See also https://dossier.univ-st-etienne.fr/dsi/www/tice/geologie/Mineraux_region/Partie2-C/terrils.html

of these products as *minerals*: "It has therefore been decided that, as a general rule, products of combustion are not to be considered as minerals in the future."¹⁴ The contradiction provoked heated debates in discussion forums and incidentally provided an excellent topic for epistemological reflections. It also raises the issue of "boundaries." Thus we can note for instance:

"Where do we draw the line between secondary shaft minerals, secondary slag minerals, secondary burning coal minerals and secondary iron cap minerals? The phenomena of crystallization/oxidation/cementation are the same."

Indeed in such places Nature is at work with the same determination as everywhere else, adapting, as in the previous case studies, its application to make crystals to environments modified by Man. The piling up of waste rock on the surface is part of these reworking as real stratigraphic units, as we argued in our essay "La signature stratigraphique de l'Anthropocène" (The stratigraphic signature of Anthropocene). We shall come back to such debate in reference to metallurgical waste. The concept of *Anthropocene*, if accepted, can shed new light on this issue. One might be led to distinguish a "noble mineralogy," that of the pure productions of Nature, from an "Anthropocene mineralogy," which breaks such boundaries.

Besides, many minerals owe their existence to the action of the biosphere (silica phytolite grasses, bacteria, algae, shellfish, vertebrates...); a somewhat mannered reasoning could lead to considering Man as a part of the biosphere, and to classifying his products among rocks or minerals of world history. However, many "mineral constructions" due to animals or plants are not very intentional, or at least not consciously.

Moreover, in what follows we would tend not to focus on the voluntary productions of human industry (we use here the concept of industry in its traditional sense), *i.e.* its finished products, but rather on the crystallizations of mineral species or *anthropogenic assimilated* species (how else to name them?), *i.e.* indebted to the action of Man to exist. Their generation may take place in the waste products of human activities, or in appropriate environments created by societies (a house for example), or even in some of the products of their industry, but without their manufacturers necessarily being aware of it (for example *hatrurite* as a component of cement...).

On a forum, we came across the following sentence: "*Beautiful to see and photograph, the salmoniac—sorry, ammonium chloride—from the burning slag heap of La Ricamarie is a fake, involuntary as it may be.*" The adjective "involuntary" used in this forum post is of great importance for our reflection. It goes back to our concept of the unconsciousness of human societies to have created, through their manufacturing activity, products which rank among minerals. We shall not take into consideration laboratories producing synthetic rubies, nor those beautiful forms of copper sulphate or any other chemicals produced in factories, or by young people curious about science out of their crystal-growing box-kits.

Here is the necessary and sufficient condition for mineral species to be included in the productions of Anthropocene: they need to owe their existence and development to the action of Man, without any conscious intention to produce them. The neoformations in the former mining galleries are part of this framework. Other examples can be found in the residues of human activities, which can be assimilated to stratigraphic units and considered of archaeological interest. This is also the case for metallurgical minerals.

¹⁴ NICKEL E.-H. et GRICE J.-D., The IMA Commission on new minerals and mineral names: procedures and guidelines on mineral nomenclature, *The Canadian Mineralogist* 36, 1998, p. 1-16.

3. Minerals from the ore processing industry

Mineral processing is the process of preparing the ore extracted from the mine: the aim is to deliver to the foundry ore as purified as possible (in pieces, grains or in the form of crushed sand), *i.e.* free of gangue and the accompanying fragments of surrounding rock. Traditionally, these establishments were called “ore washing plants”; in modern days, they are most commonly referred to as “mills”. These facilities produced waste glazes sometimes extending for miles, called *Waschhalden* in German. These industrial vestiges are sometimes subject to erosion, which carves out strange shapes—as in the silver mines of Taxco, Mexico, [fig. 14](#). But above all, they are subject to the circulation of percolating water, which dissolves the granular minerals still present in these sandy-silty materials, and re-precipitates the metallic elements in more oxidized combinations (or speciations): here is a new example of neoformations.

In Brazil, in the state of Minas Gerais, François Farges described the decanted brine in a vast retention basin for waste from the nearby iron mine. He noted white crusts around the edges made of a mixture of *hydrocerussite*, *hydrozincite* and *cadmium hydroxycarbonate*.¹⁵ The first two products are found in nature as mineral species.

At Sainte-Marie-aux-Mines, the 15th-century ore washing plant of the Sainte-Barbe mine—which left a veritable “millefeuille” of deposits of fine gravel, sand, silt and clay [[Fig. 15](#)—was the subject of an archaeological excavation spread over several years. The following paragraph may seem hard to digest for the uninitiated, but it is simply intended to show the finesse of investigation made possible by certain forms of archaeometry. Chemical analyses were carried out layer by layer in 2012¹⁶. Their results, however, deserve to be exploited mineralogically. For example, low levels of Al and especially Na rule out the presence of a significant feldspathic (therefore rocky) fraction: we are dealing with carefully sorted ores and gangues, separated from the surrounding rock. The quantitative Cu/Pb ratios bear the signature of the ores: the *tetraedrite* (argentiferous) and the *galena* (also argentiferous, but to a lesser extent). An exception is a silty-clay stratigraphic unit which contains almost exclusively lead as a “useful” metal, resulting in a 1.45 % content, not in the form of galena, but as carbonate (*cerussite*), probably of neoformation. The presence of *tetrahedrites* is also manifested by “anomalies” in antimony and arsenic. But for the latter element, the contents are such that they can only be explained by the presence in the ores of an important arsenic phase, be it *native arsenic* or *loellingite*. Nickel shows contents which refer to the presumed presence of *gersdorffite* or *rammelsbergite* as inclusions in ores. A final element draws our attention: the presence of phosphorus in proportions comparable to sulfur, in order of magnitude. It indicates the probable speciation of lead in the form of neoformation *pyromorphite*, in addition to the abovementioned cerussite. In fact, if these neoformed species are not strictly speaking those of the mineral processing industry, they nevertheless owe their existence to the operation of these workshops.

In the end, the chemical analyses of these washing residues offer us a powerful tool for the knowledge of the ores, but also of their selective sorting by means of washing, as well as of their evolution in the alteration of the washing “fines”. Mineralogy is somehow ungrateful in its

¹⁵ Conference by François Farges, *Minéraux «verts», métaux «verts», eldorados «verts», un éco-mirage? Le Brésil et ses richesses minérales revues sous le prisme du développement durable*, en ligne sur http://www.saga-geol.asso.fr/Geologie_page_conf_Bresil.html

¹⁶ Contribution by E. CAMIZULI, in FLUCK P. et coll, *Mines et métallurgie des non-ferreux en Alsace du Moyen-Age au XVI^e siècle (Altenberg/Sainte-Marie-aux-Mines, Steinbach)*, *Projet Collectif de Recherches* 2012, décembre 2012, 178 p.

addressing microscopic scale neof ormations, but at the same time quite playful in the investigations—true riddles, at times—that it imposes on researchers.

Within this "extended" category, we can also include the species present in the "red mud" from bauxite processing [fig. 16], and accumulated in retention basins. These tailings are composed of an abundant clay fraction, but also of metallic minerals such as *cancri nite*—a calcium-sodium aluminosilicate—or *hematite* Fe₂O₃, as well as iron hydroxides that retain a host of other metals, whose toxicity is a matter of debate: alumina, titanium, sodium, quicklime, fluorides, chromium, arsenic, mercury and so on.

4 ...and metallurgy

Metallurgy has produced tailings whose diversity is determined by the wide range of metals and technical progress made throughout history in different civilizations. We will focus on two examples: the iron and steel industry, and the non-ferrous metals of the copper-lead-silver triad.

Before the invention of the blast furnace, the iron and steel industry spread a quantity of waste far greater than that of the metal produced: these are industrial tailings, generally accumulated on "slag heaps." The core of these tailings—resulting from complex reactions between the iron ore in the blast furnace, its gangue, the additives added to the charge and the clay soil ("chamotte") that may have been used to coat the furnace walls—is called *slag*. In addition to the fact that slag shows remarkable flow structures and is riddled with gas bubbles, thus providing a miniaturized analogy to volcano lava, its petrographic study provides much information on the processes of this metallurgy [Fig. 17]. Observing it through binocular microscopes, or thin slice, or the polished section, like a petrograph, one can see genuine mineral species, even if a fairly large fraction of the slag mass has a vitreous structure. Among these species, an iron silicate SiO₄Fe₂, *fayalite*, predominates. It is also found in nature, in lava of basic composition. It is probably better known, in these same lava, the double silicate of iron and magnesium SiO₄(Fe, Mg)₂, called *peridot* or *olivine*, which forms an isomorphic series with *fayalite*.

With the "blast furnace revolution"¹⁷, the iron and steel industry lost less material, and iron no longer took refuge as massively in the composition of slag. This slag was then made of an essentially vitreous mass. However, in these vitreous slags, magnificent crystallizations of various natures are visible to the naked eye.

Infinitely more complex, non-ferrous metallurgy has left slags of an extremely variable composition, depending on the metals involved, the additives brought into the furnaces, such as fluxes, and ore gangues. For the copper-lead-silver triad, whose ores are frequently found alongside iron carbonate-based gangues, *fayalite* is also present in slags during medieval periods. Let us take the example of the foundry in the area called Pfaffenloch, at Ste-Marie-aux-Mines (France)¹⁸. Gert Goldenberg, using a metallographic microscope on sections of fayalitic slag, identified *nickeline*, *kutekite*, *kutinaïte* and *dyscrasite* (a silver antimonide) in microscopic crystallizations¹⁹. With the exception of the nickeline replaced by *loellingite*, here is the exact reproduction of the very original *paragenesis* of antimonides and arsenides of high temperature

¹⁷ Since the 12th cent. in Scandinavia, since the 14th et 15th cent. in Western Europe.

¹⁸ Archeological excavation led by P. Fluck, 1983, 2006, 2007, 2008.

¹⁹ GOLDENBERG G. et coll, *Metallhüttenwesen im Schwarzwald*, Thorbecke éd., 1996.

described by François Ruhlmann in the cracks of the granite of the Ballons, at the place called *Wasserfall* above the lake of Alfeld (Southern Vosges, France)²⁰.

The study of such slags deals with true archaeological issues, since these products are authentic *artefacts*. But its examination raises many other questions, as we shall see. Restricting the tailings of metallurgy to slag would be a very simplistic approach. The furnaces were the site of a true "protocol" of chemical reactions, generating many products that proved to be of no use to the founder. Thus various metals, which it was preferable to get rid of, entered into the composition of smelting "wafers" (in German *Speiss*, or "metal residues"), concentrating in generally well-crystallized forms iron, nickel, antimony, arsenic, sulphur and even a portion of the "useful" metals, which could not be removed from them, in particular copper in various forms. For those who know how to study them, these tailings are the "business cards" of the processes taking place in the furnaces. Johann Wolfgang von Goethe, a fine mineralogist, already demonstrated the great interest of studying slag, for example on samples from the Freiberg foundry, provided by his friend Herder in 1830.²¹ In this respect, the poet can be considered a precursor of Theodore Haupt, the founder of mining and metal archaeology²².

Thus, these slags, metal residues, lead incrustations or litharge (lead oxide), sometimes inadvertently deposited in the vicinity of the furnaces, participate in a wide range of products that can be described as the "spectrum of archaeometallurgical materials." Excavations at the Bonhomme silver foundry²³, from 1991 to 1994, yielded a significant catalogue²⁴: furnace walls, slag of various types, roasted or reducing ores, metal residues or *Speiss*, products of cupellation (*litharges*, fragments of cupels), lead-bearing neoformations (*bindheimite*, *massicot*), metals... [fig. 18, 19, 20, 21].

Within these products we can range the metallic oxides or salts which are regularly or "accidentally" produced at the mouth or in the vicinity of furnaces, such as the *white lead* or *ceruse* of Renaissance engineers [fig. 22: zinc oxide crystals]. In a well-documented publication of 1881, Schulze and Stelzner describe the formation of *willemite* (a zinc silicate), *tridymite* and *gahnite* (a zinc aluminate of the spinel family) in the muffles of zinc furnaces in Freiberg, particularly those of the famous Muldener Hütte foundry²⁵. They compare these neoformed minerals with species from natural environments (*e.g.* Franklin, N-Jersey), and dare to put their mode of formation into perspective with the processes of volcanic fumaroles.

In Slovenia, around the Idrija mercury mine, dozens of "squares" in the forest shelter accumulations of terracotta shards [fig. 23], remains of the distillation of mercury sulfide. These shards turn out to be incrustated with *cinabbar*. In various places in Europe, non-ferrous foundries have left impressive ruins. The inside of the furnaces is sometimes preserved, all encrusted with lead crystallizations—we found there galena in acicular crystals!—or other metals.

²⁰ RUHLMANN F., Etude métallogénique des minéralisations à Cu-Mo, Cu-As et Cu-Bi des Vosges méridionales: cas particulier de la haute vallée de la Doller, online on *Persée*

²¹ FLUCK P., Johann-Wolfgang von Goethe et la minéralogie: une passion totale, in *Goethe, le mythe et la science. Regards croisés dans les littératures européennes*, 2019, Colloques en ligne, <https://www.fabula.org/colloques/sommaire6098.php>

²² HAUPT Th, *Bausteine zur Philosophie der Geschichte des Bergbaues*, Zweite Lieferung, *Die Archäologie und Chronik des Bergbaues*, Leipzig, A. Felix éd., 1866, 76 p.

²³ It was in operation as early as the 1550s for the processing of ore from the Ste-Marie-aux-Mines mines

²⁴ FLUCK P. et FLORSCH N., L'archéologie du feu: les fonderies d'argent du Bonhomme (première partie), *Bull. Société d'Histoire du Canton de Lapoutroie – Val d'Orbey* 15, 1996, p. 9-28

²⁵ SCHULZE H. et STELZNER A., Über die Umwandlung der Destillationsgefäße der Zinköfen in Zinkspinnell und Tridymite, *Neues Jahrbuch für Mineralogie, Geologie und Palaeontologie*, Stuttgart, 1881, I, p. 120-161

5. Neoformations in slags

All these products described above were formed very quickly, by crystallization or vitrification, during the cooling of the furnace charge, or of the castings in the forehearth. However, we still have another story to tell, which is much more in line with the gradualness or slowness of many geological processes. Perhaps the most subtle form of the *Anthropocene*!

Indeed, slag, this miniature lava, systematically contains bubbles, a perfect medium for a whole range of minerals to find a hospitable place where to show their presence. Here are again authentic *neoformations*! These fine crystallizations did not escape the observation, or the magnifying glass, of certain petrologists or mineralogists of the 19th century. They can be found in relative abundance in the slags – partly bathed by the beating of the tides – of the Athenian foundries of Laurium. In these places, sea salt reacts with these highly leady materials to form chlorides, such as the *laurionite* $\text{Pb}(\text{OH})\text{Cl}$ described by Austrian mineralogist Rudolf Koechlin²⁶. Stanislas Goldsztaub, a pupil of Alfred Lacroix and my mineralogy teacher, explained its structure²⁷. A textbook case in the history of the discipline, *laurionite* was later discovered in natural environment²⁸.

The study of such materials brought a new field to mineralogy, initiated in 1896 by French mineralogist Alfred Lacroix on the ancient slag of Laurium²⁹. In 1908, L. Michel describes crystals in the slag of Poullaouen, in Brittany (France)³⁰. For the slag of the 19th-century lead and silver foundry of Vialas (Lozère, France), Cédric Lheur identified as many as 45 neofomed mineral species [fig. 24 et 25]³¹, 27 species for Poullaouen³²! Kolitsch *et al.* described as many as 110 species for the site of Maria Weitschach, near Hüttenberg, in Carinthia (Austria)³³! The Harz provided a lot of them³⁴. If a field of study thus opens up, which even extends to the science of materials, these crystallisations, when intelligently questioned, constitute a little exploited object to refine our approach to metallurgical processes (metals, additives or fluxes...), and thus shed light on the archaeology of techniques.

One can still read on a forum: «*These slag "minerals" deserve to be listed and classified, some amateurs have specialized in their harvesting and there is no reason to reject this field, which proves as interesting and varied as that of "natural" minerals found in slag. Giving them a name while waiting to find them in the natural environment doesn't seem shocking to me...* »

²⁶ KOEHLIN R., Über Phosgenit und ein muthmasslich neues Mineral vom Laurion. *Annalen des K.K. Naturhistorischen Hofmuseums*, 1887, p. 185-190.

²⁷ GOLDSZTAUB S. (1937) Crystalline structure of *laurionite*. *Comptes rendus Acad. Sci. Paris*, 204, 1937, p. 702-703.

²⁸ RUSSELL A. et HUTCHINSON A., On laurionite and associated minerals from Cornwall. *Mineralogical Magazine*, vol. 21, 116, 1928, p. 221-228.

²⁹ And in later publications, such as LACROIX A. & DE SCHULTEN A., Note sur les minéraux plombifères des scories athéniennes du Laurion, *Bull. Soc. Française de Minéralogie*, 1908

³⁰ MICHEL L., Sur la présence de quelques minéraux dans les scories anciennes de la fonderie de plomb de Poullaouen (Finistère), *Bull. Soc. Franç. de Minéralogie*, 31, 1908, p. 274-275 (en ligne sur *Gallica*)

³¹ LHEUR C., *La mine de Vialas en Lozère*, éd. d'auteur, 1997, 190 p.

³² LHEUR C., La fonderie de Poullaouen et les minéraux de scories: la redécouverte d'un « gîte », *Le Règne Minéral H.-S.* 18, 2012, p. 81-97.

³³ KOLITSCH U. et al., Die Mineralogie der weltweit einzigartigen Schlacken von Weitschach, Kärnten *Annalen des Naturhistorischen Museums in Wien. Serie A für Mineralogie und Petrographie, Geologie und Paläontologie, Anthropologie und Prähistorie*, 115, 2013, pp. 19-87

³⁴ <http://www.vfmg-freiburg.de/index.php/fotogalerie/schlackenmineralien>

If it is a delight for lovers of "micro-mounts," this mineralogy of slags and other foundry tailings, through its primary and especially secondary species (for neoformations in bubbles), is also at the origin of lively online debates, whose positions are quite understandable. Thus we could read:

"Come on, a little respect for your colleagues... Here we're dealing with minerals, not artifacts from the industry's garbage cans. The International Mineralogical Association unconditionally excludes any "anthropogenic product" such as those coloured chemicals, of proven crystalline forms, which can be found in the bubbles of slag—vulgar waste from the chemical or metallurgical or even mineralurgical industry.

Critics of "slag mineralogy" replace the names of mineral species with the designation of chemical compounds, or accompany them with the word "synthetic." In fact, the IMA, through E.-H. Nickel³⁵, excludes from the field of mineralogy species that have not been found in a natural context. This is the case for several species of Laurion, which nevertheless remain approved because of the age of their publication³⁶. The noun 'synthesis' or the adjective 'synthetic' do not seem sustainable to me, for they imply a human will to elaborate a product. In the present case, we are observing or discovering nature at work in an *anthropogenic* ecosystem, be it small (scoria) or large (a burning slag heap)³⁷. Moreover, if we accept the idea that Man is the creator of stratigraphic entities that are superimposed or interspersed (a waste heap covered by the colluvium of slopes...) to those of geological origin, we should embrace the idea of mineralogy of the Anthropocene.

It is obvious that a refusal to recognize as minerals the neoformations in slags leads to exclude all other types of occurrences (burning coalfields, old mine galleries). One can read online: *"...it will be necessary to be stricter and tell the IMA to remove all secondary minerals formed as a result of anthropic actions (Sainte Marie aux Mines, Cap Garonne... are some examples!), because why stop at metallurgical slag minerals? »*

"It should be noted that the IMA initially accepted slag minerals by trying to define certain conditions of age, absence of intentional creation... it was the recent, more complex waste that had to prompt the abandonment of their validation... The minerals of Laurion and burning slag heaps were accepted."

I think we can agree that the IMA was mistaken on this issue, or it has tried to justify itself behind a fallacious historical-archaeological shell. For why should the waste from the "industrial age" be less informative? What will become of them in a few hundred years' time? Here we come to the recurring problem of the boundaries that the proponents of a field of investigation try to draw artificially within their potential universe of study. We found this very pertinent statement on a forum:

"Where do we draw the line between secondary mine minerals, secondary slag minerals, secondary burning coal minerals and secondary iron cap minerals? The phenomena of crystallization/oxidation/cementation are the same."

³⁵ NICKEL E.-H., Definition of a mineral. *Canad. Mineral.* 33, p. 689-690

³⁶ In fact, their conservation as minerals is tolerated for species described before 1995.

³⁷ In my previous publications, I supported the idea of a *mineral ecology*; see for instance, FLUCK P., Vue nouvelle sur la géologie des Vosges moyennes d'Alsace et son apport pour l'histoire de la chaîne varisque. *Bull. Soc. Hist. Colmar*, 57, 1978/80, p. 3-76.

6. Speciation of heavy metals in soils

The case of speciation of metals in soils transcends the previous ones, especially because this process extends to the places where waste accumulates (waste tailings or slag heaps)—an environmental colonisation favoured by meteoric agents (winds, water circulation). In the immediate vicinity of the mines, waste tailings are to be found, which frequently contain a certain quantity of ore. These rock piles are washed by rainwater. Rainwater has the power to partially hydrolyse the ore; heavy metals will be transported and then redeposited downstream, at a greater or lesser distance, under new chemical combinations that are frequently crystallised. These are called "speciations," and some of them³⁸ can be considered as minerals. Their belonging to the field of mineralogy is subject to their identification as listed species, but also to delimitations in the field of the infinitely small: can nanomaterials be assimilated to minerals?³⁹ Some people are opposed to this, on the pretext that on such small buildings, physical properties can neither be perceived nor measured.

The same applies to contamination from slag heaps, such as the one in Escalette, south of Marseilles (France) [Fig. 26], which was brought to the forefront by an alarmist television program. Outside of the ruined factories, the main slag heap occupies 0.55 hectares (compared to the 17 hectares of the Rio Tinto slag heap, Fig. 27). Extensively researched records have been produced on this site by the health authorities of the Bouches-du-Rhône (France). In spite of this, a number of questions goes still unanswered as to the real sources of contamination during the operation of the foundry (from the second half of the 19th century to the first half of the 20th). How did this foundry work, how many furnaces did it have, where exactly were they located, what quantities of raw materials did they process, by what processes, when did the different concentrations of waste date? These are the questions that need to be answered in order to understand the evolution over time of metal speciation. The anomalous levels of arsenic, antimony and lead on either side of the 350-metre creeping stack are not unexpected, except that we are once again confronted with the mineralogy of *neoformations* (such as *mimetite*, a lead arsenate whose presence is not surprising).

In the valley bottoms, metallic compounds often settle with their suite of silts and clays in the manner of sediments, sometimes in the form of laminates in stratified deposits; the ions are carried by the hydrographic network which, upstream, leach or scour waste storage sites (residues from ore processing mills, foundries, chemical plants).

Partial conclusion

These minerals from the mineral industry, metallurgy, or especially those resulting from the migration of metals from production sites, make these places true natural laboratories for the study of metal *speciation*. The "time" parameter plays a pre-eminent role in these reactions or deposits: we can therefore consider these environments as recorders of the evolution over time of matter neofomed throughout the Anthropocene. This research is part of an applied science approach and enables us to describe, understand or predict the consequences of these heavy metal loads for the evolution of the biosphere, as well as its repercussions on the health of populations.

³⁸ We also encounter organic compounds, which are formed by reaction, frequently with the complicity of bacteria, with soil organic matter or living tissue, such as mercury compounds in the form of methyl mercury in the vicinity of gold mine amalgamation facilities.

³⁹ NICKEL E.-H. et GRICE J.-D., The IMA Commission on new minerals and mineral names: procedures and guidelines on mineral nomenclature, *The Canadian Mineralogist* 36, 1998, p. 1-16.

7. Metal objects in their archaeological environment, or affected by fires

In their archaeological environment, metal objects change shape, colour and density, sometimes to the point of becoming unrecognizable. Then they enter into equilibrium with the surrounding materials, or else participate with them, as a partner, in various exchanges that we call chemical reactions.

Let's take the case of Armorican copper axes. Analyses of the various oxidation products of these objects have led to the identification of a certain number of components which characterize a given chemical composition, and a crystalline state: in mineralogy, we call them mineral species. Since the crystals are small and not very visible, and frequently without any proper shape, their determination is most conveniently done using the method known as "X-ray diffraction." Thus in our tools (copper axes) coexist, variously represented, *cuprite* Cu_2O , *tenorite* CuO , *malachite* and *azurite* (carbonates), *covellite*, *chalcocite* and *bornite* (sulfides), *langite* and *brochantite* (sulfates), as well as chlorides, such as *atacamite* (which evokes the fabulous copper deposits of Chile!) $\text{CuCl}_2 \cdot 3\text{CuO} \cdot n\text{H}_2\text{O}$ and *natochite* CuCl_2 (unstable, whitish, grey in sections)⁴⁰. Add to this panoply of species the *chalconatronite* $\text{Na}_2\text{Cu}(\text{CO}_3)_2$, which has also been found on Egyptian statuettes. Armorican lead axes are not to be outdone: PbO , PbCl_2 , PbSO_4 , PbCO_3 , PbO_2 have also been found. In the field of mineralogy, these products go under the name of *massicot*, *cotunnite*, *anglesite*, *cerussite*, *plattnerite*.

We thus observe that the metallic object, once buried, returns to states close to the ores of these metals, such as they are observed in the zones of oxidation or cementation of the deposits. This observation leads us to imagine the *cycle of the metal*, starting from the (stable) ore, going to the ingot (by reduction metallurgy), to the finished object (by transformation metallurgy), unstable, which then finds its archaeological environment, favourable to its transformation into mineral species that "reproduce" the original ores. This analogy is not without interest. Our objects are authentic artefacts, but, unlike slag, they are "product artefacts," not "waste artefacts." The action of natural agents—water percolations in archaeological stratigraphic units—and various parameters (flow, PH, nature of the objects' environment...) create this range of *oxidized* agents, which are quite comparable to the crystals in slags. Once again, Nature is at work on an anthropogenic microcosm.

This category includes objects that are rapidly transformed under the action of a violent fire, in the context of natural disasters. Alfred Lacroix was a pioneer with his work on the remains of Saint-Pierre (Martinique)⁴¹. He developed a mineralogy and even a petrography of materials mainly resulting from the fire that followed the flooding of the city by the burning cloud: "This is how new rocks and minerals were born." And even if real archaeological excavations in the ruins of St-Pierre started only a century later, Lacroix's samples can be assimilated to a collection of archaeological witnesses transformed by the action of nature in its violent forms: *cuprite* crystals on the copper wires, *litharge* on the lead objects, *zincite*, *willemite* and *gahnite* on the brass objects of the Duplan house, or even the sometimes complete transformation of iron into *magnetite* [fig. 28]. Lead in reduced form appears where crystal glass used to be (the chandelier of the Cathedral of Our Lady of the Assumption).

The *aragonite* of the pearls is transformed into *calcite*, the limestone into lime. Lacroix describes the transformations of glass, the phenomena of devitrification (wollastonite...); the strange and

⁴⁰ MOHEN J.-P., *Métallurgie préhistorique. Introduction à la paléoméallurgie*. Masson, 1990

⁴¹ LACROIX A., *La Montagne Pelée et ses éruptions*, Masson éd., 1904; see particularly p. 607 *et seq.* « Les produits de l'incendie de St-Pierre ».

molten objects he studies will later inspire certain forms of surrealism, to be retrieved in the works of Salvador Dali.

The bricks house neogenous minerals, such as *pyroxene* or *tridymite*: these phenomena are not very far, in our opinion, from the processes of contact metamorphism. The lavas of the building stones themselves partially melt and secreted new minerals (*babingtonite*, *pyrrhotite*, *bytownite*, *melilite*...).

Alfred Lacroix generalized his point by evoking neocrystallizations in the products of fires, referring in particular to the objects of the castle of St-Cloud, destroyed on October 13, 1870. The integration of these types of objects into the field of archaeology is not gratuitous. Such events put an end to the life of a building, precipitating it violently into the world of archaeology... and leaving it to the investigation of mineralogists or petrographers.

8. Neoformations in or on the surface of building stones

In our first section, we witnessed the development by human societies of underground cavities that Nature has invaded with its crystallizations. This eighth section discusses the role of the built environment as a host, or "trap structure," for Anthropocene mineral species.

Saltpetre or "stone salt"⁴² forms crusts made of fibrous crystals, in cellars or storerooms, barns or stables, around humid environments. The presence of water loaded with ammonium ions (supplied more particularly by animals' urine) allows these solutes to "rise" by capillary action along the walls. Oxidised by nitrifying bacteria, these *ammonium* ions give rise to a salt, a potassium nitrate called *nitre* or *saltpetre*. It should be noted that *nitre* occurs naturally in certain arid regions of the world, in soils loaded with organic matter. Saltpetre, which used to be highly sought-after as a raw material for powder, was also used for salting. Which explains the importance of the saltpetre maker's trade. Some people harvested it... where it was found, in the places we have just mentioned. Others produced it artificially in workshops--a true saltpetre industry, and as such beyond the scopes of mineralogy.

As a more general rule, the circulation of water by capillary action in porous rocks (sandstone, calcareous tuff) is at the origin of the crystallization of sulfates, carbonates or chlorides, sometimes with the complicity of microorganisms, or air pollution: *gypsum*, *thenardite* Na_2SO_4 , *mirabilite*⁴³ or Glauber's salt $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ ⁴⁴, *natron* $\text{NaCO}_3 \cdot 10\text{H}_2\text{O}$... **Figure 28** is a table to help memorize the compositions of the main types of salts.

It is always remarkable to note that certain mineral species are formed indifferently in Nature or in "Man-modified Nature," which restricts the cleavage between the mineralogy of geological formations and that of the Anthropocene. All in all, in the preceding examples we observe only the determination of Nature (obviously governed by physico-chemical processes) to respond to the demands of its environment. It so happens that the above-mentioned salts are also produced naturally, in lagoons, salt lakes, temporary lakes or in the residual deposits resulting from their

⁴² D'ALEMBERT, DIDEROT, *L'Encyclopédie*, tome 14, 1751, p. 577-580.

⁴³ Also described by René Weil as neoformation in a gallery at the Gabe-Gottes mine in Ste-Marie-aux-Mines (France), which then appeared "as if covered in snow."

⁴⁴ JEANNETTE D. et coll., *La conservation de la pierre monumentale en France*, CNRS éd., 1992, 240 p.; BROMBLET Ph., *Memento sur les altérations de la pierre*, <http://pierresud.brgm.fr>. One may find several other references on the Web.

evaporation: Aral Sea and Caspian Sea, Death Valley in California, Great Salt Lake and many other places, or in the Saharan depressions for *natron* mainly (the "Egyptian soda")...

In the carbonate family, *calcite* or *aragonite* play an important role in the displacement/precipitation of matter, usually related to runoff water. Thus, the Nîmes aqueduct in France had to be progressively abandoned following the loss of flow, due to the crystallization, in its inner lumen, of a thick calcite concretion.⁴⁵

9. A mineralogy of materials

The miracle of the potter. In the potter's kiln, or in industrial tile-making, minerals are made and undone, starting from an initial composition that includes silica, possibly feldspar or mica, and the clay minerals that form the essential matter of the "earth." A strange mutation occurs during firing, which transforms these plastic and deformable materials into a hard and durable ceramic. It is felt that the study of the neofomed minerals in the kiln will allow us to understand the "miracle of the potter" that has remained unexplained for so long in history. The pioneering study of a population of amphorae by Véronique Walter⁴⁶ showed the presence, in the mass of the shard, of *sanidine*, *diopside*, *gehlenite*, *wollastonite* and *hematite*. These species—well known to mineralogists, including collectors—can be divided into primary minerals (inherited, present in the paste or in the "degreaser"), species that appeared during firing, and those formed secondarily. Even better: the stability ranges of these minerals according to the temperature field could be determined by experimentation; the concomitant presence of several species allows to evaluate with a certain approximation the **baking temperature**. However, such value is to be used with caution: mineralogical readjustments within the material and in a given "climate" (temperature, general composition of the material, ambient air, confinement, etc.) require time, and the importance of this latter parameter cannot be underestimated.

The analogy between firing in the potter's kiln and, in nature, the thermal metamorphism of a schistose series in contact with a granite is quite striking. With their horn-like structure, *hornfels*—the ultimate term for contact metamorphism—can be compared to some refractory ceramics. Man reproduces what Nature makes in its own "laboratories"! Obviously, ceramics are manufactured artefacts. However, even if the potters are not aware of the nature of the minerals they make, these cannot claim to belong to the natural mineral species. On the other hand, mineralogy, understood as a science using a proven method of investigation, can legitimately be led to take an interest in these products, and to designate them by the same name as the analogues provided by Nature.

Johann Wolfgang von Goethe was perfectly aware of the importance of understanding the mineralogy of ceramics. He even hoped that, by raising the temperature of the kiln in a porcelain factory, he would experience the phenomena of rock melting⁴⁷.

⁴⁵ GUENDON J.-L., LEVEAU Ph., Dépôts carbonatés et fonctionnement des aqueducs romains: The upstream basin of the Vallon des Arcs on the Arles aqueduct (Bouches-du-Rhône, France), Gallia editions, 2005 available online at Persée

⁴⁶ WALTER V., *Étude pétrographique, minéralogique et géochimique d'amphores gauloises découvertes dans le Nord-Est de la France, contribution à l'étude des matériaux, des technologies et des provenances*, Doctoral Thesis in Ancient History, University of Strasbourg (France), 1988.

⁴⁷ FLUCK P., Johann-Wolfgang von Goethe et la minéralogie: une passion totale, in *Goethe, le mythe et la science. Regards croisés dans les littératures européennes*, 2019, Colloques en ligne, <https://www.fabula.org/colloques/sommaire6098.php>

Some of the mineralogical constituents of ceramics, which are very discreet in its petrography, are nevertheless quite important for research. We are referring here to the iron oxides produced by firing (the red colour of the brick is not lost on anyone!). Fine particles of *magnetite* Fe_3O_4 "capture" the earth's magnetic field and "fossilise" it, as it were, when the material left in the kiln cools down. Geophysicists use this property to date the operation of the kiln, using the method known as *archaeomagnetism*.

It is interesting to look back at the encyclopaedia "Gart der Gesundheit" (Garden of Health) from early 16th century. The tiles (*tegula*) are listed under the heading of stones, as is the *terra sigillata*.

Minerals in cement. Cement introduces us to another textbook case that has some similarities with the previous one. We shall analyse it to foster reflection. A construction material, cement is made from three main raw materials: limestone, clay (composed of aluminous minerals) and sand (composed of silica) [Fig. 29]. Obviously the elements recombine themselves when fired: they form microscopic crystals "discovered" by researchers who studied the petrography of the material, as one would study a rock. Thus silica combines with calcium to form a silicate of lime $(\text{CaO})_3\text{SiO}_2$ called *alite*, a compound that exists in nature in the form of a mineral species called *hattrurite*, discovered in 1977 in a context of contact metamorphism. This composition is moreover quite close to *wollastonite* $(\text{CaO})_2\text{SiO}_2$, a little less calcareous, but much better known by mineralogists. However, cement also hosts *calcite*, *gypsum*, MgO *periclase*—a mineral well known in nature—, and aluminous minerals—notably a calcium aluminate—, which house the aluminium initially provided by the clay fraction of the raw material. Mercury is involved in the *clinkerization* process. Finally, *portlandite* $\text{Ca}(\text{OH})_2$, a kind of "slaked lime" also described in nature, is one of the essential products of cement weathering!

Unlike ceramics, cement does not really have a "rock" equivalent in nature, with the possible exception of certain calcsilicate hornfels. Nonetheless, Man has been able to create materials through this industry that can be assimilated to an "Anthropocene rock", without even being aware that these materials will contain authentic minerals. Among these, some share this identity with natural compounds, while others may have no equivalent in nature. Such considerations lead us to include these entities within the field of mineralogical research.

10. A mineralogy of the biosphere?

The "Gart der Gesundheit" is full of descriptions of stones that form inside the eyes or skulls of certain animals—in the heads of toads, for example—which constitute the matter of pearls, sponges and shells, or their mother-of-pearl. It describes succin as a gum that flows from trees. Add to this the phytoliths of cereals, or the mineral salts concentrated by plants. A whole mineralogy of the biosphere... but that's another thing! These biogenic species have their equivalents in nature. Nickel and Grice, for the IMA, put it this way⁴⁸: "Some biogenic substances, such as hydroxylapatite in teeth, whewellite in urinary calculi⁴⁹, or aragonite in the shells of molluscs, also exist as minerals formed by geochemical processes, and therefore are regarded as valid minerals." *Whewellite*, for example, was discovered and described in the copper-silver

⁴⁸ NICKEL E.-H. et GRICE J.-D., op. cit.

⁴⁹ Note that *whewellite* was discovered and described by UNGEMACH in the copper-silver paragenesis of the Sylvestre mine vein at Urbeis (Bas-Rhin, France).

paragenesis of the Sylvestre mine vein in Alsace (France), by its mining manager—and remarkable mineralogist—Henri Ungemach⁵⁰.

Conclusions

We could almost conclude from all this that the Anthropocene is full of minerals! Through these different case studies, we have just reviewed a certain number of environments characterized by the presence of mineralogical species. Some were obtained artificially without their creators being aware of it, others were manufactured by Nature in host sites set up by Man—be it intentionally or not. Nature thus digests the works of Man, through a kind of retroactive effect.

Taken from an analytical perspective, the question is not an easy one. In the first place, the birthplaces of such species are to be considered. These can be:

- Trap structures or Man-made accommodation sites (mines, houses, underground tombs...); a mine gallery is a negative stratigraphic entity, delivered to the action of the elements!
- Waste fields or waste heaps; a slag heap is an anthropogenic stratigraphic unit whose interior is delivered to Nature; each piece of waste from a slag heap, each buried metal object, can be considered as an artefact in turn delivered to Nature which exerts its action there;
- Human residences abandoned by humans in a slow (archaeological sites) or violent (fires, volcanoes) process.
- The territory itself (for metal migrations in surface formations).
- Factories (in the case of ceramic or cement kilns) which produce artificial materials, but whose constituent species may be of interest to mineralogists, as much as to researchers in materials science, as they give rise to interesting epistemological reflections.

With the exception of factories, these types of sites can be likened to true mineral **ecosystems**, in which sometimes the biosphere interferes. Such ecosystems took place during the Anthropocene, after Man turned away from the landscape modifications he had just produced (excavations, dumps, sediments, burying of objects, which thereby acquired archaeological status...). From that moment on, Nature acts alone and manufactures... minerals. The physico-chemical laws are universal and apply in all environments!

Beyond these considerations on the "generation" of these species, it is still necessary to make a distinction between the realizations proper to the forces of Nature (those mentioned in the previous chapter), and those unconsciously manufactured by Man. We have excluded from these considerations the intentional productions of crystallized species, such as candy sugar—which is the subject of a chapter in the "stones" section of the "Gart der Gesundheit"⁵¹—, or the calcium carbide from the Bellegarde or Allasac factories, whose smell is quite familiar to speleologists. Or even the potassium alum crystals that children "grow" from a kit that their parents have found in a toy department: there, the growth of the crystal is done on purpose! Even though thick wafers of

⁵⁰ UNGEMACH H., Notes sur les cristaux de whewellite rencontrés dans un filon métallifère alsacien, *Bull. Soc. Franç. Minéral.*, 32, 1909, p. 20-34.

⁵¹ He also describes a stone called *mumia*, composed of aloe myrrh and balm "that thwarts death", with which mummies were embalmed.

nically crystallized silicon, industrially obtained in American companies, can be found in mineral exchanges.

We can now wonder whether Man "makes" geological formations himself, in the sense of the Earth sciences. The answer is "no" in the absolute sense. What Man brings does occupy the volume of stratigraphic entities, but its content is not recognised by petrography, with a few exceptions⁵². Indeed, cement, concrete and earth are Man-made igneous rocks (produced by the action of fire), just as residues from ore washing or sediments modified by accidental pollution could be classified as sedimentary rocks. If, on the other hand, the question embraces the creation of minerals by human societies, the answer must be "yes", since the species that Man generates, with or without the complicity of Nature, are in no way different from those produced in nature's laboratories. This article attempts to argue just this!

Captions for illustrations



Fig. 1—Coralloid aragonite in a former Altenberg mine gallery at Ste-Marie-aux-Mines (France). Photo P. Fluck

⁵² See « La signature stratigraphique de l'Anthropocène ». Examples include ore washing sediments, or sedimentation at the bottom of dam lakes...



Fig. 2—In a miniature, a miner's statuette with coralloid aragonite, in a showcase in the museum of Eisenerz, Styria (Austria). Photo P. Fluck



Fig. 3—Salt concretion in the underground facilities of a mine in Romania. Photo P. Fluck



Fig. 4—Concretion containing iron sulfate in the Engine shaft at Grandfontaine (Alsace, France).
Photo H. Bari



Fig. 5—An arsenate: picroparmacolite *in situ* in a former Neuenberg mine gallery at Ste-Marie-aux-Mines (France). Note the insect caught in the needles of the mineral. Photo P. Fluck



Fig. 6—Fluckite on tetrahedrite bearing quartz, 5 x 2 cm, Giftgrube mine, Ste-Marie-aux-Mines (France). Photo P. Fluck



Fig. 7—Raenthalite, 5.5 x 3 cm, Ste-Marie-aux-Mines (France). Photo P. Fluck



Fig. 8—A geotope: organs in rhyolitic lava, Scandola nature reserve (Corsica, France). Photo P. Fluck



Fig. 9—The wall of the deepest room of the tomb of Padiamenopoe, necropolis of Thebes (Egypt).
Photo P. Fluck

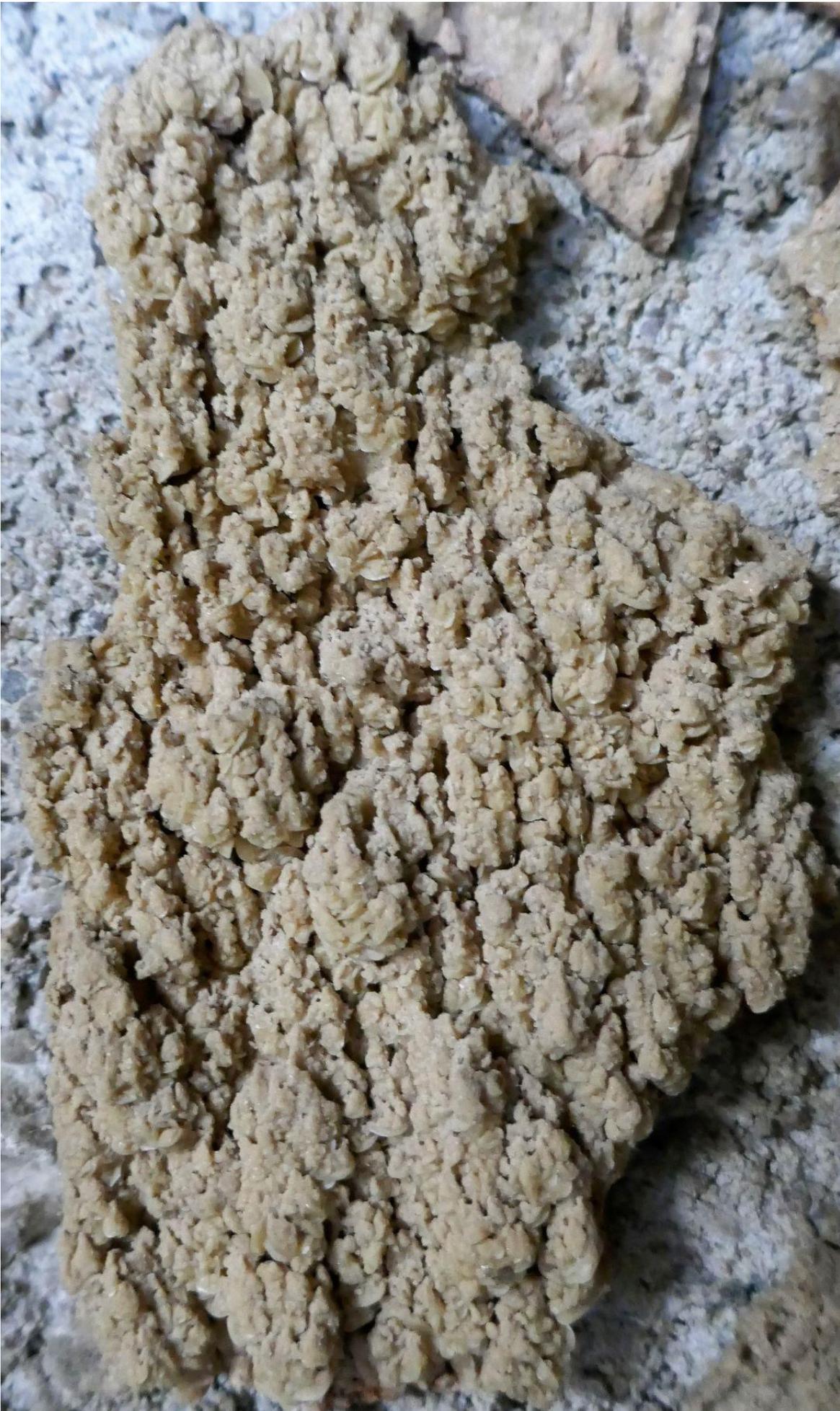


Fig. 10—Potassium tartrate or *wine stone*. Photo P. Fluck



Fig. 11—Western slag heap of the Couriot shaft in St-Étienne (France). Note the burned parts. Photo P. Fluck



Fig. 12—Realgar (arsenic sulfide) from a slag heap around St-Étienne (France), 4.5 x 3 cm. Photo P. Fluck



Fig. 13—Arsenolite (arsenic oxide) from a slag heap around St-Étienne (France), 6 x 4 cm. Photo P. Fluck



Fig. 14—Erosion phenomena in a silver mine tailings dump in Taxco (Mexico). Photo P. Fluck



Fig. 15—The laminated "mille-feuilles" from the tailings of the St. Barbe mine washing plant (late 15th century) at the Altenberg (Ste-Marie-aux-Mines, France). Stratigraphic section made during an archaeological excavation. Photo P. Fluck

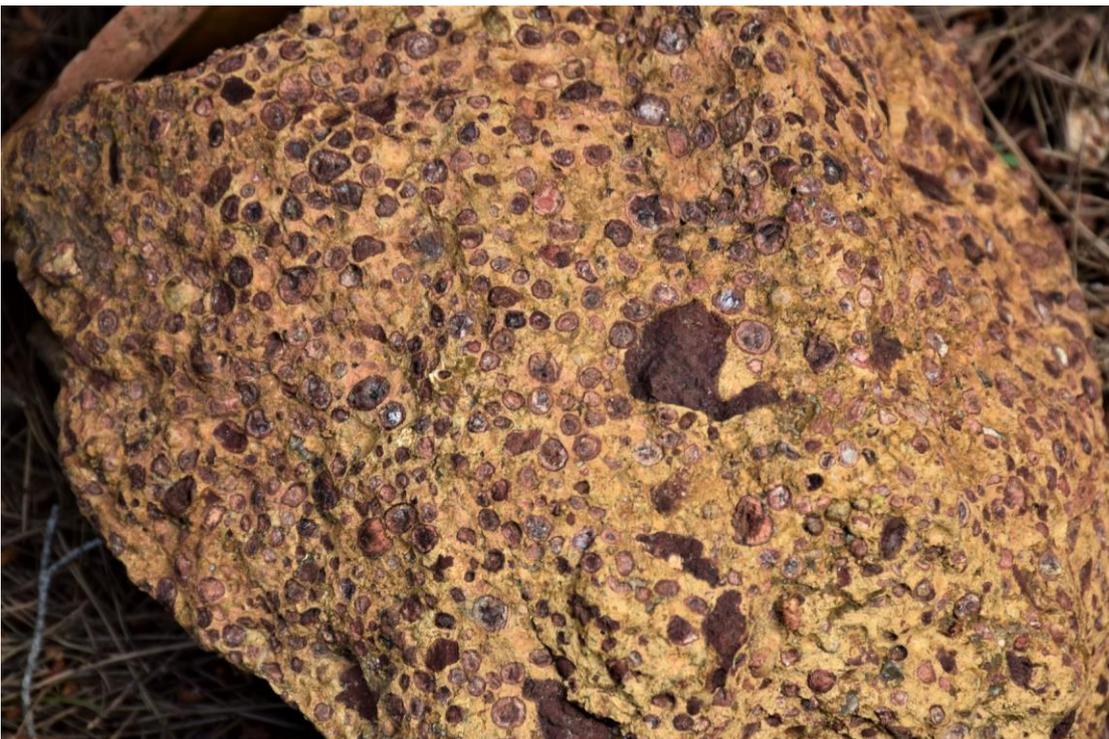


Fig. 16—Bauxite block from Les Baux (France), observed *in situ* (approximate length: 30 cm). Photo P. Fluck



Fig. 17—Fayalitic slag, Saales foundry (7th century), France, 8 x 6 cm, excavations F. Magar. Photo P. Fluck

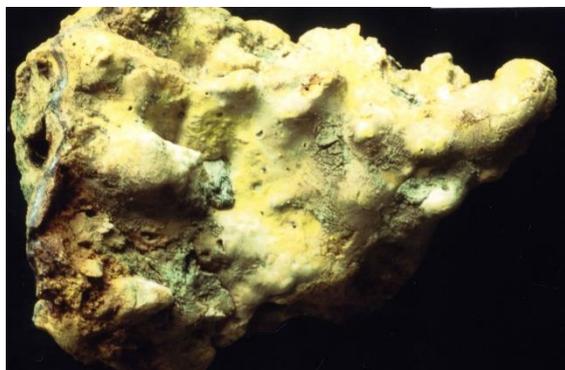


Fig. 18—Piece of massicot (5 x 3 cm), excavation of the lead and silver foundry (16th century) at Le Bonhomme (Alsace, France), 1994. Photo P. Fluck



Fig. 19—Piece of litharge (4 x 4 cm), excavation of the lead and silver foundry at Le Bonhomme (Alsace, France), 1994. Photo P. Fluck



Fig. 20—Fragment of a granite furnace wall, which has become bubbly (4 x 4 cm), excavation of the lead and silver foundry at Le Bonhomme (Alsace, France), 1994. Photo P. Fluck



Fig. 21—Density stratified metal “Speis”, which filled a basin about 30 cm in diameter; sawn section; excavation of the Lauterupt lead and silver foundry (16th century) near Ban-de-Laveline (Lorraine, France), 1995. Photo P. Fluck



Fig. 22—Zincite crystal (16 cm) from a furnace in Silesia (Poland). Photo P. Fluck



Fig. 23—Accumulation of shards of ceramic vessels for mercury distillation, Idrija (Slovenia). Photo P. Fluck



Fig. 24—Minerals in the slag cavities of the Vialas foundry (Lozère, France): langite (blue) and anglesite (white) at the bottom of a vacuole. Photo C. Lheur



Fig. 25—Minerals in the slag cavities of the Vialas foundry (Lozère, France): the same picture as Fig. 24, closer up: small green crystals of lautenthalite can be seen. Photo C. Lheur



Fig. 26 – Escalette site, in Marseille (France). Photo P. Fluck



Fig. 27—The slag heap at the Rio Tinto foundry. Photo P. Fluck

		Cations				
		Ca	Na	K	Al	NH ₄
A n i o n s	Cl		Sel	Potasse (minérale)		Salmiac
	S ₀₄	Gypse	Sel de glauber	Alun		
	C ₀₃	[Chaux]	[Soude] ou natron	Potasse (végétale)		
	N ₀₃	Salpêtre (nitre)		Salpêtre (nitre)		
	B ₀₄		Borax		Ulexite	

**Le
tableau
des sels**

Fig. 28—Salt Chemistry Table. Concept P. Fluck, DAO F.-Florimond Fluck

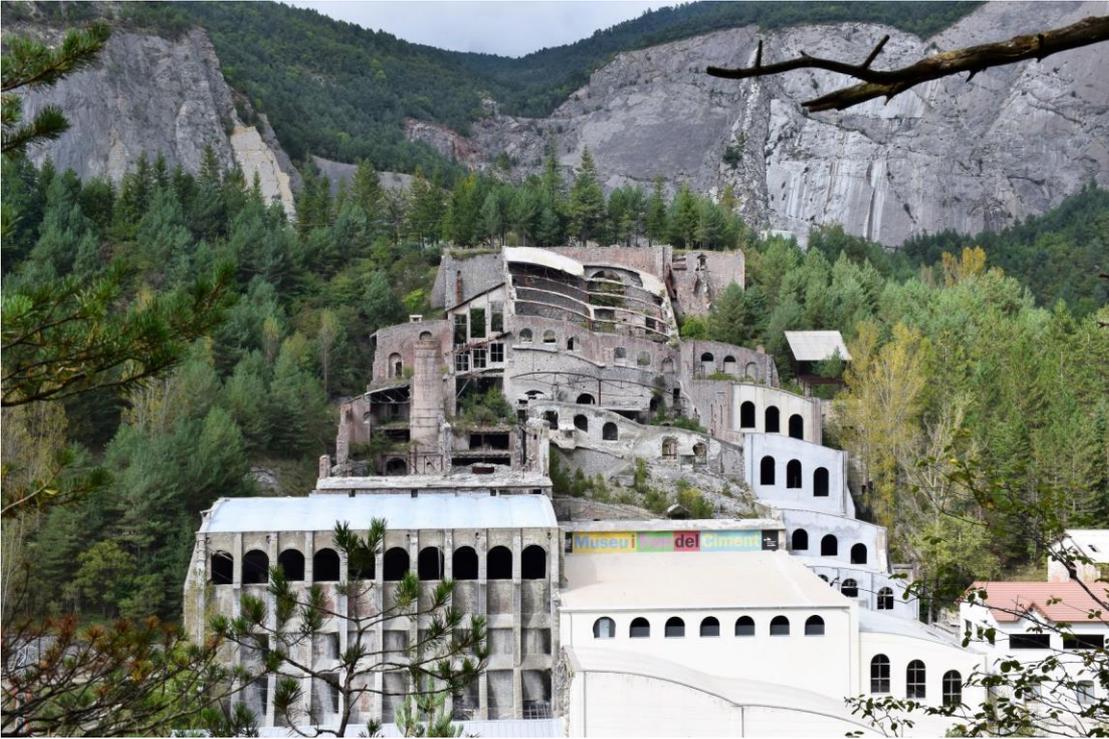
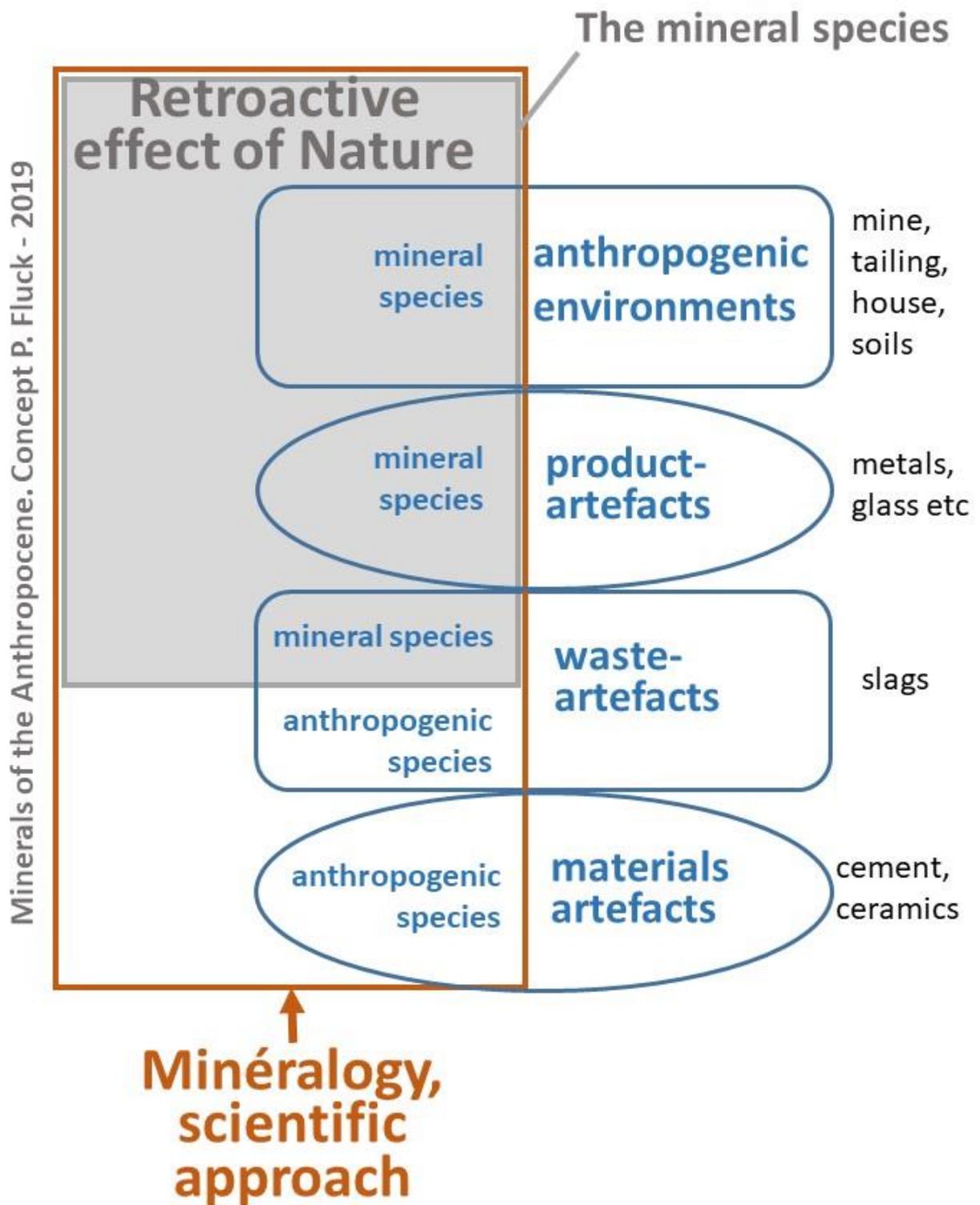


Fig. 29—Cement factory in Clot del Moro, Catalonia (Spain). Photo P. Fluck



Unnumbered table: organization chart to be used as a basis for reflection for a "mineralogy of the Anthropocene."