This is a preprint, the final version is subject to change, of the American Mineralogist (MSA)
Cite as Authors (Year) Title. American Mineralogist, in press.
(DOI will not work until issue is live.) DOI: http://dx.doi.org/10.2138/am-2017-6045

Highlights and Breakthroughs:

Defining Minerals in the Age of Humans

Peter J. Heaney

Dept. of Geosciences

Penn State University

University Park, PA 16802

Email: pjheaney@psu.edu

This is a preprint, the final version is subject to change, of the American Mineralogist (MSA)
Cite as Authors (Year) Title. American Mineralogist, in press.
(DOI will not work until issue is live.) DOI: http://dx.doi.org/10.2138/am-2017-6045

ABSTRACT

In their Overview article, Hazen et al. (2017) ponder mineral evolution within the so-called Anthropocene. Very much like the concept of the Anthropocene itself, which has its avid supporters and its committed debunkers, the authors' consideration of human participation in the diversification of minerals will stimulate its admirers and incite some skeptics. After establishing guidelines for "anthropogenic minerals", Hazen and colleagues conclude that the Age of Humans already has expressed itself uniquely within the mineralogical record. If their arguments are accepted alongside those of Zalasiewicz et al. (2014), the Anthropocene materializes as a period of intense diversification, in contrast to its conventional image as an epoch of destruction and homogenization.

This is a preprint, the final version is subject to change, of the American Mineralogist (MSA)
Cite as Authors (Year) Title. American Mineralogist, in press.
(DOI will not work until issue is live.) DOI: http://dx.doi.org/10.2138/am-2017-6045

LUCIUS: What will he find out there, doctor?

Close-up of Zaius. His face is a mask, his tone enigmatic.

ZAIUS: His destiny.

Mineralogists of a certain age may recognize this exchange from the 1968 script of *Planet of the Apes*, a film that expertly parlayed the dread of humankind's imminent demise into a blockbuster movie. In the famous closing shot, George Taylor -- the astronaut played by Charlton Heston -- curses humanity as he enters the Forbidden Zone and sees the Statue of Liberty buried chest-high in sand. "Oh, my God! I'm back! I'm home…You maniacs! You blew it up!" he exclaims when he realizes that his voyage has propelled him forward in time but not in place.

The question of what we might find were we to (re)visit the Earth millions of years hence has advanced from science fiction to serious geoscience, and the apprehension in our expectation is embodied by the concept of the Anthropocene. For those geologists who have themselves been on an interstellar excursion for the past two decades and are unaware of the debate, the Anthropocene is a proposed addition to the Geological Time Scale that would terminate the Holocene Epoch at some point in the recent past and mark a new epoch that signals the emergence of humans as a planet-shaping force. First pitched by Nobel Laureate Paul Crutzen (Crutzen and Stoermer 2000), the concept of the Anthropocene has caught the fancy of both geoscientists and the public, and the International Commission on Stratigraphy (ICS) is busily considering the arguments for and against (Monastersky 2015).

This is a preprint, the final version is subject to change, of the American Mineralogist (MSA)
Cite as Authors (Year) Title. American Mineralogist, in press.
(DOI will not work until issue is live.) DOI: http://dx.doi.org/10.2138/am-2017-6045

Skeptics object that the Anthropocene is more appropriately considered a cultural than a scientific phenomenon (Autin and Holbrooke 2012; Gibbard and Walker 2014). Where an earlier generation regarded nuclear war as the likely instrument of our own extinction, today we look at the transformations that we have wrought on the Earth – from global climate change to the exhaustion of clean water to the depletion of energy and mineral resources – as the means by which we will cede this world to the next species. Consequently, the Anthropocene has emerged as an unusually effective meme for our collective anxiety over humanity's unsustainable appetite. A recent paper in *Science* makes the case for its geologic integrity as well (Waters et al. 2016).

When Hazen and co-workers published their notions of mineral evolution (Hazen et al. 2008; Hazen and Ferry 2010), believers in the Anthropocene naturally wondered how the Age of Humans might register within this new paradigm. Would an astromineralogist examining geological strata 50 million years in the future identify the impact of *Homo sapiens* in the rock record through an excursion in Earth's mineral diversity? Stealing a beat on the originators of the mineral evolution thesis, Jan Zalasiewicz and colleagues published a paper in 2014 to promote the argument that the explosion of anthropogenic minerals since the dawn of technology has created a new, eleventh stage in Hazen's model (Fig. 1). The catch in this treatment appears in that curious phrase – "anthropogenic minerals."

Mineralogists are just now coming to terms with the idea that many valid mineral species may form only biogenically. The International Mineralogical Association has not formally moved on this topic, but introductory mineral texts

This is a preprint, the final version is subject to change, of the American Mineralogist (MSA)
Cite as Authors (Year) Title. American Mineralogist, in press.
(DOI will not work until issue is live.) DOI: http://dx.doi.org/10.2138/am-2017-6045

(e.g., Dyar et al. 2008; Nesse 2012) now qualify their definitions to include biominerals without apparent harm to the field. But are we prepared to take the next step and accept synthetic crystals as minerals? Do we privilege humans alongside bacteria and fungi as natural participants within the Earth system? Zalasiewicz et al. (2014) argue that the time has come to take that fateful stand, and they offer a Proposed Amendment to Mineral Classification:

> We suggest, therefore, that new anthropogenic minerals should be listed and classified in their own right, perhaps as a special category within the IMA's formal listing, and perhaps in conjunction with relevant scientific bodies working on synthetic materials…
>
> The new systematics would apparently need to comprise such major categories as 'natural minerals', 'biominerals', 'anthropominerals' (metals and alloys, ceramics and glasses, cement, concrete, bricks and slags, polymers and plastics, composite materials, semiconductors, synthetic 'minerals', nanomaterials and so on), as well as transitional materials in between. This would be a significant challenge to mineralogists (including technical mineralogists) and materials scientists.

If you view these suggestions with alarm and your mind has leapt from Charlton Heston wrestling orangutans to Haim Topol belting a verse of "Tradition!" from

This is a preprint, the final version is subject to change, of the American Mineralogist (MSA)
Cite as Authors (Year) Title. American Mineralogist, in press.
(DOI will not work until issue is live.) DOI: http://dx.doi.org/10.2138/am-2017-6045

Fiddler on the Roof, then the Outlook article by Hazen et al. (2016) will be music to your ears.

Taking a step back from the radical – though thought-provoking – arguments presented by Zalasiewicz et al. (2014), Hazen and colleagues ponder mineral diversification in the Anthropocence if we play by the IMA rulebook. Rather than include synthetic semiconductors as minerals, Hazen et al. ask how many minerals that currently are accepted by the IMA can be considered to be truly anthropogenic? Even when the IMA constraints are imposed, the task is tricky for the reason that delineating biogenic and abiogenic minerals can be a challenge (Perry et al. 2007). If a mineral is an inadvertent by-product of human activity, do we consider it artificial or natural? Hazen et al. carefully explain their criteria for labeling minerals as anthropogenic, and based on their classification system, they identify 206 minerals as markers of the Anthropocene. Does their more restricted interpretation support the imposition of an eleventh stage in Hazen's mineral evolution scheme? The answer is left as an exercise for the reader.

Acceptance of the arguments of Hazen et al. – or, even more, those of Zalasiewicz et al. (2014) – requires us to moderate an assessment of the Anthropocene that is totally dismal. Most people regard the Anthropocene as an epoch in which Earth's diversity has been catastrophically diminished and homogenized at the hands of humanity. As a result of our destruction of entire habitats, from prairie grasslands to tropical rainforests to coral reefs, we are laying the groundwork for what some have labeled "the Sixth Extinction" (Kolbert 2014). We have normalized the Earth's surface by leveling mountains for ore extraction

This is a preprint, the final version is subject to change, of the American Mineralogist (MSA)
Cite as Authors (Year) Title. American Mineralogist, in press.
(DOI will not work until issue is live.) DOI: http://dx.doi.org/10.2138/am-2017-6045

and by moving massive quantities of soil for construction and agricultural purposes. The revolutions in transportation and in information technology over the last century have reduced even humanity's cultural diversity.

From a materials perspective, however, the Anthropocene is an era of unparalleled diversification. As I write this review, the Inorganic Crystal Structure Database lists 187,093 crystal structures, and that number increases weekly. These include compounds that never before existed on Earth, in the Solar System, maybe in the universe, and they were created by human ingenuity. Materials science in the Age of Humans is one regime that has seen an explosive expansion of species; it is a rare rainbow that spans the graying of the current era. Mineralogists may decide to celebrate the fertility of the Eleventh Stage of Mineral Evolution, if only to counter the desolation of the Anthropocene in every other regard.

REFERENCES

Autin, W. J. and Holbrook, J. M. (2012). Is the Anthropocene an issue of stratigraphy or pop culture? GSA Today, 22, 60-61.

Crutzen, P. J. and Stoermer, E. F. (2000). The Anthropocene. Global Change Newsletter. 41, 17-18.

Dyar, M. D., Gunter, M. E., and Tasa, D. (2008). Mineralogy and optical mineralogy. Mineralogical Society of America, Chantilly, VA.

Gibbard, P. L. and Walker, M. J. C. (2014). The term 'Anthropocene'in the context of formal geological classification. Geological Society, London, Special Publications, 395, 29-37.

Hazen, R. M. and Ferry, J. M. (2010). Mineral evolution: Mineralogy in the fourth dimension. Elements, 6, 9-12.

Hazen, R.M., Grew, E., Origlieri, M.J., and Downs, R.T. (2017) On the mineralogy of the "Anthropocene Epoch". American Mineralogist, in press.

Hazen, R.M., Papineau, D., Bleeker, W., Downs, R.T., Ferry, J.M., McCoy, T.J., Sverjensky, D.A. and Yang, H. (2008) Mineral evolution. American Mineralogist, 93, 1693-1720.

Kolbert, E. (2014). The sixth extinction: An unnatural history. Bloomsbury, London.

Monastersky, R. (2015). Anthropocene: the human age. Nature, 519, 144-147.

Nesse, W. D. (2012). Introduction to mineralogy. Oxford University Press, New York.

Perry, R.S., Mcloughlin, N., Lynne, B.Y., Sephton, M.A., Oliver, J.D., Perry, C.C., Campbell, K., Engel, M.H., Farmer, J.D., Brasier, M.D. and Staley, J.T. (2007) Defining biominerals and organominerals: direct and indirect indicators of life. Sedimentary Geology, 201, 157-179.

Waters, C.N., Zalasiewicz, J., Summerhayes, C., Barnosky, A.D., Poirier, C., Gałuszka, A., Cearreta, A., Edgeworth, M., Ellis, E.C., Ellis, M. and Jeandel, C. et al. (2016) The Anthropocene is functionally and stratigraphically distinct from the Holocene. Science, 351, aad2622.

Zalasiewicz, J., Kryza, R. and Williams, M. (2014). The mineral signature of the Anthropocene in its deep-time context. Geological Society, London, Special Publications, 395, 109-117.

This is a preprint, the final version is subject to change, of the American Mineralogist (MSA)
Cite as Authors (Year) Title. American Mineralogist, in press.
(DOI will not work until issue is live.) DOI: http://dx.doi.org/10.2138/am-2017-6045

FIGURES

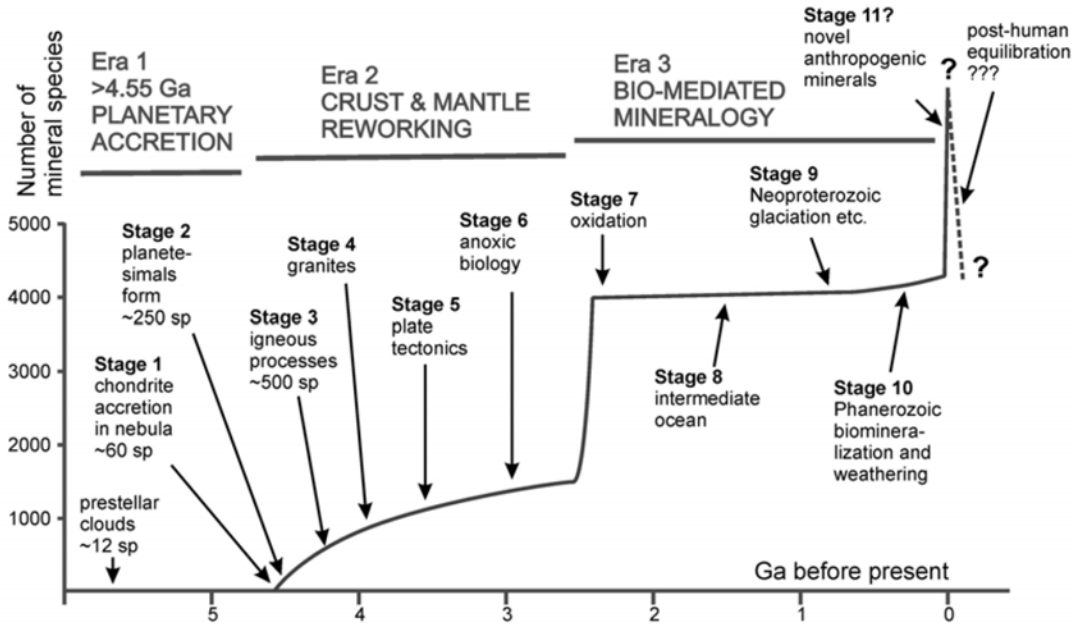

Fig. 1 – The evolution of minerals on Earth, drawn after data in Hazen et al. (2008). From Zalasiewicz et al. (2014). Reprinted with permission. [Heaney needs to get permission from the Geological Society of London.]