Highlights and Breakthroughs

(invited Commentary for American Mineralogist)

# Mineral Evolution and Earth History

**Dwight C. Bradley**

U.S. Geological Survey, 4210 University Drive, Anchorage, AK 99508, U.S.A.

## Abstract

The field of mineral evolution—a merger of mineralogy and Earth history—coalesced in 2008 with the first of several global syntheses by Robert Hazen and coworkers in the American Mineralogist. They showed that the cumulative abundance of mineral species has a stepwise trend with first appearances tied to various transitions in Earth history such as the end of planetary accretion at ca. 4.55 Ga and the onset of bio-mediated mineralogy at ca. >2.5 Ga. A global age distribution is best established for zircon. Observed abundance of zircon fluctuates through more than an order of magnitude during successive supercontinent cycles. The pulse of the Earth is also recorded, albeit imperfectly, by the 87Sr/86Sr composition of marine biogenic calcite; the Sr-isotopic ratio of this mineral reflects the balance of inputs of primitive strontium at mid-ocean ridges and evolved strontium that drains off the continents. A global mineral evolution database, currently in the works, will greatly facilitate the compilation and analysis of extant data and the expansion of

research in mineralogy outside its traditional bounds and into more interdisciplinary realms.

**Keywords:** Mineral evolution, Earth history, detrital zircon geochronology

## Mineral Evolution and Earth History

The study of Earth history lends itself to two complementary big-picture approaches: plate reconstructions and analysis of global secular trends. Plate reconstructions have a geographic focus. Each reconstruction must be pieced together from worldwide information about rocks of appropriate age that bear on tectonic setting or paleogeographic position. Deeper in the past, reconstructions get more difficult, and less likely to be correct, because the ancient rock record is sparse and fewer research tools are available. But another problem is that even a perfectly accurate set of plate reconstructions wouldn't necessarily reveal much about the evolution of the Earth System. This is where the second, time-based approach comes in: analysis of global secular trends. Geologic data that can be tracked through time include numerical model results (Pollack 1997—global heat production; Korenaga 2006—mantle rheology), isotopic trends (Veizer and Mackenzie 2003—seawater $^{87}Sr/^{86}Sr$; Valley et al. 2005—$\delta^{18}O$ in zircon), geochemical trends (Golden et al. 2013—Re in molybdenite); quantities of mineral resources (Meyer 1988; Goldfarb et al. 2010), age distributions of rock types (Condie et al. 2009—granite), and censuses of tectonic settings (Bradley 2008—passive margins). A recent review of geologic secular trends was published by Bradley (2011).

This note celebrates a succession of papers on geologic secular trends under the recently named banner mineral evolution. The seminal work was a 2008 overview by Robert Hazen and coworkers in The American Mineralogist. They found that the cumulative abundance of all mineral species has a stepwise trend with first appearances tied to major transitions in Earth history. Three main intervals can be recognized (Hazen et al. 2008): the era of planetary accretion (pre-4.55 Ga), the era of crust and mantle reworking (4.55 to 2.5 Ga), and the era of bio-mediated mineralogy (>2.5 Ga to present). Superimposed on this broad framework, Hazen et al. (2008) highlighted ten shorter intervals such as the Great Oxidation Event and Snowball Earth, some of which overlap and (or) have uncertain age limits. Exactly where the initiation of modern-style plate tectonics fits into this scheme is still debated, with interpretations ranging from as early as 4.4 to 4.5 Ga (Harrison 2009) to as recently as ca. 1.0 Ga (Stern 2005). Since their 2008 paper, Hazen and his colleagues have focused on the minerals of uranium and thorium (Hazen et al. 2009), mercury (Hazen et al. 2012), carbon (Hazen et al. 2013a), beryllium (Grew and Hazen, 2014), and the clay minerals (Hazen et al. 2013b). Each of these groups of minerals yields insights into different aspects of Earth's evolution, for example U and Th as heat producers, U and C as redox indicators.

First appearances of minerals are only part of the story; each mineral species has its own age distribution through Earth history. With single-crystal U-Pb or Pb-Pb ages now numbering in the millions, zircon already holds a special place in this sphere of research. Global age distributions of zircon ages from igneous rocks, detrital zircon ages from sedimentary or metasedimentary rocks, and detrital zircon aegs from modern river sands are remarkably similar (Bradley 2011). The river-sand compilation in Figure 1 shows a remarkable, semi-periodic fluctuation in the abundance of zircon ages. The highs and lows have been linked to the supercontinent cycle, although their particular significance is controversial. Two possibilities are that zircon age populations record variations in preservation of rocks (Cawood et al. 2013), or changes in the global subduction flux (Bradley 2011). Robust compilations of the age distributions of tectonically or paleogeographically sensitive minerals such as halite, ikaite, scapolite, nepheline, glaucophane, and ruby would be of particular interest to researchers who develop and test plate reconstructions. It remains to be seen if the global age distributions of minerals such as these can be accurately predicted.

Another long-established thread in mineral evolution involves the isotopic composition of particular minerals as a function of age. One of the most informative isotopic records, so far, is the $^{87}Sr/^{86}Sr$ composition of marine biogenic calcite, a mineral that is precipitated from coeval seawater. The Sr isotopic ratio reflects the balance of inputs of primitive strontium at mid-ocean ridges and of evolved strontium that drains off the continents (Veizer and Mackenzie 2003). Seawater strontium may hold the key to the zircon conundrum noted above because ratios are not subject to the same uncertainties as censuses.

Other aspects of mineral evolution are outlined in a white paper titled "Needs and opportunities in mineral evolution research" by Hazen et al. (2011). One the most energizing ideas is a plan for a Mineral Evolution Database, tied to www.mindat.org and designed to serve the entire geology community. The database already has 3000 dated localities, with plans for expansion. As more research focuses on tracking geologic features and variables through time, we can expect many new breakthroughs regarding evolution of the Earth System.

**References cited**

Bradley, D.C. (2008). Passive margins through Earth history. Earth-Science Reviews, 91, 1-26.

Bradley, D.C. (2011) Secular trends in the geological record and the supercontinent cycle. Earth-Science Reviews, 108, 16-33.

Campbell, I.H., Allen, C.M., 2008. Formation of supercontinents linked to increases in atmospheric oxygen. Nature Geoscience 1, 554–558. doi:10.1038/ngeo259.

Cawood, P.A., Hawkesworth, C.J., and Dhuime, B. (2013) The continental record and the generation of continental crust. Geological Society of America Bulletin, 125, 14-32, doi:10.1130/B30722.1.

Cawood, P.A., Hawkesworth, C.J., and Dhuime, B. (2013) The continental record and the generation of continental crust. Geological Society of America Bulletin, 125, 14-32

Condie, K.C., Belousova, E., Griffin, W.L., and Sircombe, K.N. (2009) Granitoid events in space and time: constraints from igneous and detrital zircon age spectra. Gondwana Research, 15, 228-242.

Golden, J., McMillan, M., Downs, R.T., Hystad, G., Goldstein, I., Stein, H.J., Zimmerman, A., Sverjensky, D.A., Armstrong, J.T., and Hazen, R.M. (2013) Rhenium variations in molybdenite ($MoS_2$): Evidence for progressive subsurface oxidation. Earth and Planetary Science Letters, 366, 1-5.

Goldfarb, R.J., Bradley, D.C., and Leach, D.L. (2010) Secular variation in economic geology. Economic Geology, 105, 459-465.

Grew, E.S., and Hazen, R.M. (2014) Beryllium mineral evolution. American Mineralogist, 99, 999-1021.

Harrison, T.M. (2009) The Hadean crust: evidence from >4 Ga zircons. Annual Review of Earth and Planetary Sciences, 37, 479-505.

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

Hazen, R.M., Ewing, R.C., and Sverjensky, D.A. (2009) Uranium and thorium mineral evolution. American Mineralogist, 94, 1293–1311.

Hazen, R.M., Bekker, A., Bish, D.L., Bleeker, W., Downs, R.T., Farquhar, J., Ferry, J.M., Grew, E.S., Knoll, A.H., Papineau, D., Ralph, J.P., Sverjensky, D.A., and Valley, J.W. (2011) Needs and opportunities in mineral evolution research. American Mineralogist, 96, 953–963.

Hazen, R.M., Golden, J., Downs, R.T., Hysted, G., Grew, E.S., Azzolini, D., and Sverjensky, D.A. (2012) Mercury (Hg) mineral evolution: A mineralogical record of supercontinent assembly, changing ocean geochemistry, and the emerging terrestrial biosphere. American Mineralogist, 97, 1013–1042.

Hazen, R.M., Downs, R.T., Jones, A., Kah, L., and Oganov, A. (2013a) The mineralogy of carbon. In R.M. Hazen, J. Baross, R.J. Hemley, and A. Jones, Eds., Carbon in Earth, 75, 7–46. Reviews in Mineralogy and Geochemistry, Mineralogical Society of America, Chantilly, Virginia.

Hazen, R.M., Sverjensky, D.A., Azzolini, D., Bish, D.L., Elmore, S.C., Hinnov, L., and Milliken, R.E. (2013b) Clay mineral evolution. American Mineralogist, 98, 2007-2029.

Korenaga, J., 2006. Archean geodynamics and thermal evolution of Earth: Archean geodynamics and environments. AGU Geophysical Monograph Series 164, 7–32.

Meyer, J. (1988) Ore deposits as guides to geologic history of the Earth. Annual Reviews of Earth and Planetary Science, 16, 147-171.

Pollack, H.N. (1997) Thermal characteristics of the Archean. In De Wit, M.J., and Ashwal, L.D. Eds., Greenstone Belts, p. 223–232. Clarendon Press, Oxford.

Stern, R.J. (2005) Evidence from ophiolites, blueschists, and ultrahigh-pressure metamorphic terranes that the modern episode of subduction tectonics began in Neoproterozoic time. Geology, 33, 557–560.

Valley, J.W., Lackey, J.S., Cavosie, A.J., Clechenko, C.C., Spicuzza, M.J., Basei, M.A.S., Bindeman, I.N., Ferreira, V.P., Sial, A.N., King, E.M., Peck, W.H., Sinha, A.K., and Wei, C.S. (2005) 4.4 billion years of crustal maturation: oxygen isotope ratios of magmatic zircon. Contributions to Mineralogy and Petrology, 150, 561–580. DOI 10.1007/s00410-005-0025-8.

Veizer, J., and Mackenzie, F.T. (2003) Evolution of sedimentary rocks. Treatise on Geochemistry, 7, 369-407.

**Figure Caption**

**Figure 1.** Global age distribution of detrital zircons from the sands of major rivers, from Bradley (2011) after Campbell and Allen (2008). The maxima correponds to times of supercontinent assembly, the minima to times of supercontinent tenure.

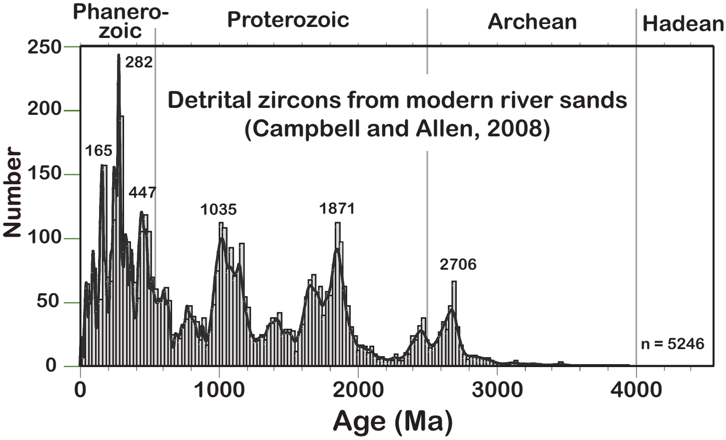


Figure 1, highlight & breakthrough on Mineral Evolution