Mineral evolution and its educational implementation

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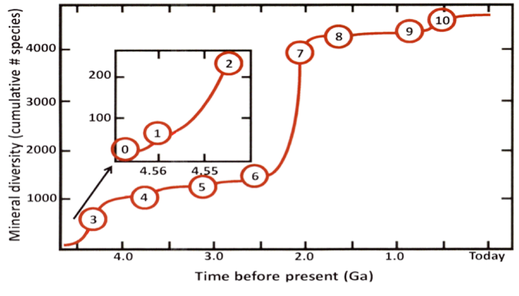
I. Introductory Remarks

- Mineral evolution: the idea that mineral species increase in diversity, abundance, and complexity over the formation of a terrestrial body.
- Earth is a unique mineralogical specimen: ~5000 minerals
  - ~10x the minerals found elsewhere in the Solar System
  - Only ~1500 can be explained by geochemical or geophysical processes
  - Remaining ~3500 species must be from life (oxygenated atmosphere or other biogeochemical processes)
- Mineral evolution provides new ways to view biotic/abiotic interactions, use minerals as biosignatures, classify terrestrial bodies, and study mineral systems.
- Adds another layer to mineralogy, and with that how it could be framed and taught (Hazen et al., 2008).

- Notable universities and museums have added mineral evolution concepts to their courses/exhibits.
- We are interested in understanding the extent to which these concepts are being taught.
- We have developed a survey to distribute to the mineralogy teaching community to gain statistical information on mineral evolution occurrence in higher education.
- We are working with Tellus Science Museum on their Annual Mineral Symposium (Spring 2023) to gain similar insight into informal education.



The Stages of Mineral Evolution (Carnegie Institute, 2022)

II. Mineral Evolution

Identifies three principal mechanisms of mineralogical diversification.

1. Elemental segregation and concentration: settling of elements due to density/differentiation
2. Increasing ranges of variables (P, T, a): more possible combinations = more minerals
3. Life: actively pushes systems out of equilibrium

Typically organized into three "eras" and ten "stages"

Before the 1st Era: Early Universe (> 4.6 Ga)

- Original 12 pre-solar micro-/nano-minerals: "Ur"-Mineralogy
- Diamond first; graphite, carbides, nitrides, etc

1st Era: Planetary Accretion/Formation

- **Stage 1: Unaltered Chondrite (>4.56 Ga) 60 minerals**
  - Melting/cooling in solar nebula
- **Stage 2: Achondrite & Planetesimal Alteration (~4.56 – 4.55 Ga)**
  - ~250 minerals
  - Solid material condenses; low-grade metamorphism, differentiation, water out of melt reacting with solids
  - Feldspars, significant quartz, clays, zircons

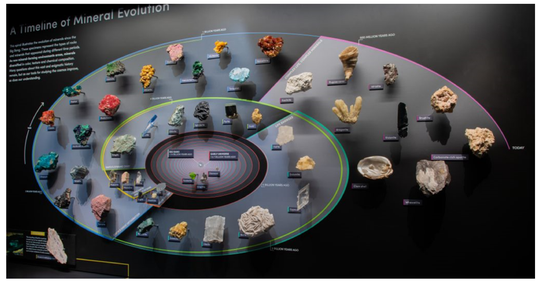
2nd Era: Crust & Mantle Reworking

- **Stage 3: Igneous Rock Evolution (~4.55 – 4 Ga) 300 - 420 minerals**
  - Partial melting, fractional crystallization of magma, and new P/T combinations
  - ~300 minerals for dry body (stage Mercury/Moon may have reached)
  - ~420 minerals for wet body (stage Mars may have reached)
- **Stage 4: Granitoid / Pegmatite Formation (~3.5 – 3 Ga) 1000+ minerals**
  - Complex pegmatites formed through multiple cycles of working/melting as originally hot/mafic Earth cools
  - Differentiation; increasingly felsic compositions isolated out of melt
- **Stage 5: Plate Tectonics (>3 Ga) ~1500 minerals**
  - Tectonics = new volcanism, hydrothermal reworking, new P/T combinations
  - Sulfides and sulfosalts
  - Furthest geochemical and geophysical processes can explain

3rd Era: Biologically Mediated Mineralogy

- **Stage 6: Anoxic Archean Biosphere (~3.9 – 2.5 Ga) ~1500 minerals**
  - Life with anoxic environment = few new minerals
  - Minerals precipitating out from oceans (carbonates, sulfates, evaporites, BIFs)
- **Stage 7: Paleoproterozoic Oxidation (~2.5 – 1.85 Ga) ~4500 minerals**
  - Photosynthesis = O in atmosphere/shallow ocean
  - Increased number of oxidation states of mineral-forming elements
  - Up to 3000 new oxides, hydroxides, and carbonates
- **Stage 8: Intermediate Ocean (~1.85 – 0.85 Ga) ~4600 minerals**
  - "boring billion", few new minerals
  - life continues to slowly change ocean chemistry
- **Stage 9: Snowball Earth (~0.85 – 0.54 Ga) ~4600 minerals**
  - Glacial cycles dominating - ice technically most common mineral
  - Slowing of biogeochemical processes = few new minerals
- **Stage 10: Phanerozoic Biomineralization (~0.54 – 0 Ga) ~5000 minerals**
  - Further evolution of complex life = new biominerals (bones/shells)
  - Rise of the terrestrial biosphere = minerals from root processes, dried animal feces, hydration of existing minerals (clays)

III. Education



AMNH's "A Timeline of Mineral Evolution" Display (Finnin, 2021)

Institutions Where Mineral Evolution is Being Taught:

Universities

- **University of Arizona**
  - Mineralogy (2019) - Dr. Bob Downs
  - Two lecture days (1 week) summarizing Dr. Robert Hazens' earlier literature much like in Section II.
- **University of British Columbia**
  - Introductory Mineralogy (2021) - Dr. James Scoates
  - 1 of 6 learning goals in syllabus: "Evaluate the diversity with geologic time of minerals on Earth ... through the concept of "mineral evolution"
  - Final full week of instruction
- **Rensselaer Polytechnic Institute**
  - Earth Materials (2019) - Dr. E. Bruce Watson
  - First lecture titled "Earth, states of matter, Earth materials, and mineral evolution"
- **George Mason University**
  - Mineralogy (2019) - Dr. Julia Nord
  - Required readings on mineral evolution
  - Dr. Hazen is guest lecturer at end of course

Museums

- **American Museum of Natural History**
  - New 2021 Hall of Gems and Minerals has permanent exhibit on mineral evolution / life's impact on mineral diversity, with mineral evolution concepts throughout hall
  - Mineral evolution video titled "How many minerals does Earth have" displayed in hall and online
- **University of Arizona Gem and Mineral Museum**
  - Moved to new space in 2020 with first gallery upon entry being the "Mineral Evolution Gallery"
- **Natural History Museum of Vienna**
  - In 2017 integrated its special exhibit of "The evolution of minerals" into its permanent collection.

IV. Survey

- A recent survey of higher education mineralogy teaching revealed that 3% of respondents listed mineral evolution as one of the most important concepts learned in a mineralogy course.
- We want to generate detailed results on the extent to which mineral evolution concepts appear in higher education, as recent surveying lacks questions that would provide this.
- Survey is currently under IRB review and will be made with Google Forms. Distribution plans are TBA (will most likely be through the Mineralogical Society of America's email list for mineralogy educators, as well as individually to relevant faculty in the U.S.)

Survey Questions Pertaining to Mineral Evolution

16. On a scale of 0-5, how familiar are you with the concept of mineral evolution? (Sliding Scale 0-5)
    0: Never heard of it ---> 5: Teach it or are very familiar with it

17. On a scale of 0-5, to what extent is mineral evolution taught in your institution's mineralogy course(s)? (Sliding Scale 0-5)
    0: It is not mentioned ---> 5: The course is framed around it

18. What benefits might accrue from incorporating mineral evolution concepts into the teaching of mineralogy? (Write-In)

19. What drawbacks might accrue from incorporating mineral evolution concepts into the teaching of mineralogy? (Write-In)

V. Tellus Symposium

- Working with Tellus Science Museum in Cartersville, GA on their annual Mineral Symposium in Spring 2023, where the theme will be Mineral Evolution.
- Guest speakers: Robert Hazen & Shaunna Morrison - Mineral Evolution research leaders from the Carnegie Institute
- Organizing roundtable discussions to congregate academics, k-12 teachers, and college students; the implementation of mineral evolution into curriculum, ideas for effective conveyance of concepts, and what information is essential will be discussed.

References