Annual Progress Report for the DDE-Funded Project

Reporting Period: July 1, 2024 to June 30, 2025

Prepared by: Robert M. Hazen

1. Project Title: Completing the "Evolutionary System of Mineralogy" [Seed Grant Funding Project (GJ-C03-2023-001)]

2. Project Deliverables:

The principal deliverables for this grant are the manuscripts of the final 5 parts of the evolutionary system of mineralogy, to be published in 12 parts. In addition, this grant supports development of open-access mineral data resources, analytical and visualization methods, and training and mentorship of early-career scholars. In Year 1 we have made significant progress on all these deliverables.

Please note that this report pertains only to work on the evolutionary system of mineralogy. The more expansive effort associated with the Carnegie DDE Research Network Node is reviewed in a separate report.

3. Summary of Work Completed During the Reporting Period:

In the past year our team, including two co-investigators (Carnegie Institution data scientist Dr. Anirudh Prabhu and Rutgers University mineralogist Prof. Shaunna Morrison), collaborator Prof. Xiaogang Ma at the University of Idaho, and early-career scholars Mark Bermanec (University of Graz, Austria) and Jiyin Zhang (University of Idaho), have made significant progress.

We have two newly published manuscripts on mineral evolution themes.

- Morrison, S.M., Prabhu, A., and Hazen, R.M. (2024) An evolutionary system of mineralogy. Part VIII. The evolution of metamorphic minerals. *American Mineralogist*, **109**, 1760-1784. This paper, the 8th in the evolutionary system series, documents the occurrences of 1220 metamorphic minerals. The paper includes links to open-access data resources on the modes of 2785 metamorphic rocks and to the distribution of minerals among 8 classes of metamorphic rocks.
- Hazen, R.M., and Wong, M.L. (2024) Open-ended versus bounded evolution: Mineral evolution as a case study. *PNAS Nexus*, 3(7), pgae248. This work exploits large and growing data resources on mineral evolution to demonstrate the inexorable increase of mineral complexity through more than 4.6 billion years of planetary evolution. A key finding is that mineral evolution appears to be limited in the maximum possible complexity—a characteristic that is

different from biological evolution.

Several other manuscripts related to this project are now in preparation.

- "An evolutionary system of mineralogy—Part IX: Near-surface aqueous processes." Led by early-career scientist Marko Bermanec, Part IX of the system is by far the most complicated, as it traces near-surface water-rock interactions through Earth history. Unlike the previous parts, we anticipate 3 major papers in Part IX. These sections will focus on the nature of hydrogen in mineral crystal structures, the nature of mineral-forming fluids with an emphasis on T-P-X conditions, and the distinctive paragenetic modes reflected in mineral formation. Extensive data tables on crystallographic properties, formation processes, compositions, and other attributes will accompany this major series of manuscripts. Several manuscripts are nearing first draft stage.
- "An evolutionary system of mineralogy—Part X: Microbial biomineralization." The paper, in collaboration with Prof. Hailiang Dong (China University of Geoscience, Beijing), will address complex topic of microbial production of minerals, including directed mineralization of magnetite in magnetosomes and carbonates for buoyancy control, indirect production of minerals through redox metabolisms, and expulsion of minerals in toxic environments. Extensive data tables related to microbe/mineral associations have been prepared.
- "An evolutionary system of mineralogy—Part XI: The Great Oxidation Event." We are excited that Postdoctoral Associate, Dr. Yanzhang Li, will arrive from Prof. Yan Li's laboratory to begin a 2-year fellowship at the Carnegie Institution, where he will lead the effort to complete Part XI. This work will examine the more than 2000 minerals that arose following Earth's atmospheric oxygenation. Extensive data resources will be amplified with network analysis and other visualizations.

Given these developments, we anticipate that several manuscripts will have been submitted in Year 2 of this project.

<u>4. Description of the tasks undertaken by individuals involved in the project</u>

- Principal Investigator Robert Hazen will continue to contribute to all parts of the evolutionary system's development, compiling data, analyzing data, and writing manuscripts.
- Co-Investigator Dr. Anirudh Prabhu will continue to produce network graphs and other analytical and visualization aspects of the system.
- Co-investigator Prof. Shaunna Morrison will continue to contribute to all aspects of the system.
- Graduate student Marko Bermanec will be the lead author on the complex series of papers related to Part IX.
- Prof. Hailiang Dong will be collaborator (with a postdoctoral fellow to be

named) on Part X of the system.
- Postdoctoral Fellow Dr. Yanzhang Li will be the lead author on Part XI of the system.

5. Changes in staff at the Co-PI level:

Prof. Shaunna Morrison has moved from her Carnegie Research Associate position to a tenured professorship at Rutgers University in New Jersey. She continues to be fully engaged in this effort.

6. Compliance with the Work Plan

The key deliverables in this Seed Grant are manuscripts and related talks, as detailed in sections 3, 4, and 7 of this report. Here is a brief timeline divided semi-annually:

PART/TASK	24/II	25/I	25/II	26/I	26/II	27/I
Part VIII (the evolution of metamorphic minerals)						
Completed	X					
Part IX (the evolution of aqueous minerals)						
Data Assembly	X	X	X			
Data Analysis		X	X	X		
Manuscript 1			X	X		
Manuscript 2				X	X	
Manuscript 3					X	X
Part X (Microbial mineral evolution and the anoxic biosphere)						
Data Assembly	X	X	X			
Data Analysis			X	X		
Manuscript				X	X	
Part XI (Mineral evolution following the Great Oxidation Event)						
Data Assembly			X	X		
Data Analysis				X	X	
Manuscript					X	X
Part XII (Biominerals of the Phanerozoic Eon: Rise of the terrestrial biosphere)						
Data Assembly				X	X	
Data Analysis					X	X
Manuscript						X
DDE-Themed Conference Sessions						
	GSA;AGU	EMC; IGC	GC;GSA;AGU	IMA;GC	GSA;AGU	GC

7. Outreach

Robert Hazen continues to present numerous public lectures, departmental seminars, conference talks, and media events (podcasts; TV; video) related to mineral evolution. In the past year, his speaking events have included:

1. Hazen: August 20, 2024: "A missing law: mineral evolution as a case study." The Hallimond Lecture of the Mineralogical Society of Great Britain and Ireland. European Mineralogical Conference, Dublin, Ireland.
2. Hazen: August 19, 2024: "Mineral informatics." Keynote. European Mineralogical Conference, Dublin, Ireland.
3. Hazen: August 27, 2024: "Mineral informatics." DDE Keynote. International Geological Congress, Busan, South Korea.
4. Hazen: September 25, 2024: "Open-ended versus bounded evolution: Mineral evolution as a case study." Geological Society of America Annual Meeting, Anaheim CA. [Keynote]
5. Hazen: October 9, 2024: "Minerals, Music, and a Missing Natural Law." The John Wesley Powell Lecture, The Cosmos Club, Washington DC.
6. Hazen: November 17, 2024: "A missing natural law of evolution: Minerals, fossils, and the second arrow of time." Calvert Marine Museum, Solomons, MD. Link: https://youtu.be/JZ9PrzGZwRg
7. Hazen: December 9, 2024: "Minerals as a case study of an abiotic evolving system: Bounded versus open-ended evolution." American Geophysical Union Annual Meeting, Washington, DC.
8. Hazen: February 20, 2025: "Mineral evolution and the search for critical resources, life's origins, and time's second arrow." Caltech GeoClub, Pasadena CA.
9. Hazen: April 11, 2025: "Mineral evolution and a missing law of nature." York University, Toronto, Canada.
10. Hazen: April 12, 2025: "The evolutionary system of minerals." Royal Ontario Museum, Toronto, Canada.
11. Hazen: May 4, 2025: "Mineral evolution and a missing law of nature." Canadian Micro Mineral Association, Brock University, Canada.
12. Hazen: May 5, 2025: "The evolutionary system of minerals." Canadian Micro Mineral Association, Brock University, Canada.
13. Hazen: May 14, 2025: "The evolutionary system of minerals." GAC-MAC, Ottawa, Canada.

Public Media Presentations:

Big Think Templeton Podcasts

1. Mineral evolution: https://www.youtube.com/watch?v=XwA9wEQ8DxM
2. Devil's advocate: https://www.youtube.com/watch?v=VQNAEec9W38
3. Missing Law: https://www.youtube.com/watch?v=lepxTr9zKDc&t=105s
4. Minerals and Alien Life: https://www.youtube.com/watch?v=es6Cs5V-M7A
5. Earth's Colors: https://www.youtube.com/watch?v=LBh758B92nw

Quanta Youtube Interviews (June 2025)

Release pending

NOVA (TV) Youtube Interview for the new series, "Particles of Thought" (June 2025)

Release pending

Wisconsin Public Radio, "To the Best of Our Knowledge" podcast (October 2024)

https://www.ttbook.org/interview/why-we-need-new-theory-life

8. Benefits to DDE

All manuscripts, talks, and other contributions prominently feature acknowledgement of DDE, including the DDE logo where appropriate. The outputs of this modest Seed Grant will reach many thousands of readers and audience members.

9. Articles that have been published or are in press, which cite or acknowledge DDE:

- Morrison, S.M., Prabhu, A., and Hazen, R.M. (2024) An evolutionary system of mineralogy. Part VIII. The evolution of metamorphic minerals. *American Mineralogist*, **109**, 1760-1784. https://doi.org/10.2138/am-2023-9004
- Hazen, R.M., and Wong, M.L. (2024) Open-ended versus bounded evolution: Mineral evolution as a case study. *PNAS Nexus*, 3(7), pgae248. https://doi.org/10.1093/pnasnexus/pgae248

10. Databases, software tools, platforms, services, standards, and other outputs generated through the project funding.

- Extensive open-access data files associated with Morrison et al. (2024) on the evolution of metamorphic minerals: https://pubs.geoscienceworld.org/msa/ammin/article/109/10/1760/636064/An-evolutionary-system-of-mineralogy-Part-VIII-The

11. Problems/issues

Perhaps the major challenge has been the delayed start of funding for this effort. One promising early-career scientist could not be hired in 2023 as a result. However, we are thrilled to have Dr. Yanzhang Li joining the program in August 2025.

As to the science, there have been no unanticipated difficulties. However, we have come to realize that the final 4 parts of the evolutionary system are challenging in new ways. Part IX is a vast topic requiring at least 3 manuscripts. Part X requires the expertise of geomicrobiologists. Part XI deals with more than 2000 mineral species—by far the greatest number of any part. But we are addressing each of these issues.

12. Budget Utilization

The Year 1 budget has been devoted principally to travel to DDE-related sessions at IGC, AGU, and EMC. We have deferred spending some of the funds to support Dr. Li when he begins his postdoctoral fellowship in August 2025.

Project PI Signature

Signature: R. M. Hazen

Print Name: Robert M. Hazen

Date: July 29, 2025