

Final Narrative Report
Research Programs
(Science & Engineering Research and Medical Research)



Report Date: September 7, 2018

<p>GRANTEE INSTITUTION NAME:</p> <p>Carnegie Institution for Science, Geophysical Laboratory</p>	<p>PROJECT DESCRIPTION OR TITLE:</p> <p>The Co-Evolution of the Geo- and Biospheres: An Integrated Program for Data-Driven Abductive Discovery in the Earth Sciences</p>
<p>PROJECT LEADER:</p> <p>Name: Robert M. Hazen Title: Senior Staff Scientist, Geophysical Laboratory, and Executive Director, Deep Carbon Observatory Phone Number: 202-478-8962 Email: rhazen@ciw.edu</p>	<p>REPORTING CONTACT:</p> <p>Name: Shaunna M. Morrison Title: Geophysical Laboratory Keck Project Manager Phone Number: 202-478-8983 Email: mmeyer@carnegiescience.edu</p>
<p>PROJECT TIME PERIOD: From: 1/1/2015 To: 6/30/2018</p>	

RESEARCH IMPACTS: *(Please describe up to three of the most significant scientific or other achievements from the Keck grant (one short paragraph each))*

The principal objectives of this grant were: (1) to create the Deep-Time Data Infrastructure—an open-access suite of data resources, analytical tools, and visualization methods that would link Earth, space, and life science data related to the evolution of Earth and other terrestrial bodies; (2) apply these resources to understanding the co-evolution of the geosphere and biosphere. A longer-term aspiration was to create an international community of like-minded scientists, especially diverse early-career scholars, who will foster a new culture of data sharing and data-driven discovery. Accordingly:

- 1) We established the Deep-Time Data Infrastructure (see: dti.carnegiescience.edu), which includes links to new and expanded data resources (e.g.: ruff.info/evolution; mindat.org; paleobiodb.org), as well as powerful analytical and visualization methods.
- 2) We applied these resources to numerous problems related to Earth’s co-evolving geosphere and biosphere. Applications to understanding Earth’s earliest multi-cellular life led to the discovery of a previously unrecognized mass extinction; application to the prediction of new mineral forms led to the first specific predictions and discovery of Earth’s “missing” minerals; applications to the mineralogy of the Anthropocene Epoch generated hundreds of international news stories with an estimated 1 billion internet hits.
- 3) We organized and convened the international 4D Workshop: Deep-Time Data-Driven Discovery (June 4-6, 2018; Washington DC), with 110 participants from 12 countries. The active participation of the diverse attendees, as well as more than \$250,000 in funding support from 9 foundations and organizations, revealed a strong interest in pursuing this exciting direction with enhanced funding.

Please submit a list of publications, and patents related to the project. Please provide the abstracts to the two most significant publications related to this grant.

At the end of this document please see the “Keck Project CV,” which lists all relevant contributions, as well as two selected abstracts (though the choice of “most significant” was difficult).

Number of	
Peer Reviewed Publications	62 (of which 16 are now in review)
Non-Peer Reviewed Publications (excluding abstracts)	Our work also resulted in 3 widely read press releases that generated >1000 press stories in >25 languages stories, with an estimated >1 billion “reads”
Patents Submitted	0
Patents Awarded	0

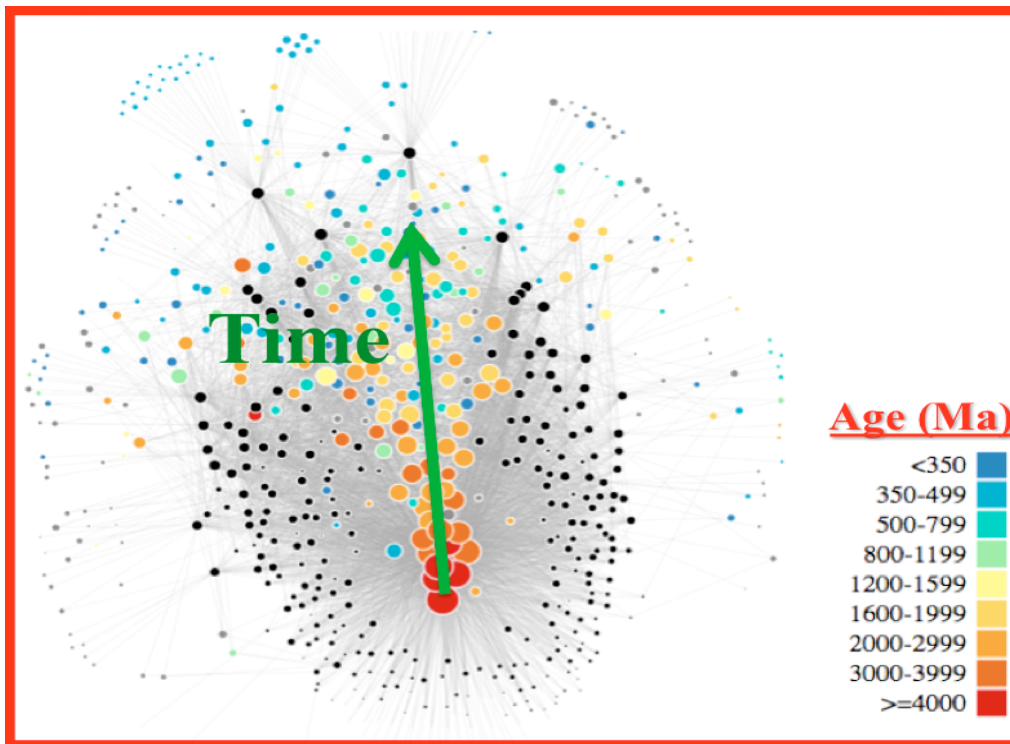
Please cite any honors and awards received by the institution, principal investigator or other key personnel, including students, relevant to this project.

Awards/Honors:

- Knoll, A (2017) Doctor of Science honoris causa, American Museum of Natural History
- Knoll, A (2018) Sven Berggren Prize, Royal Physiographic Society, Sweden
- Knoll, A (2018) GSA Geobiology and Geomicrobiology Division Award
- Ma, X (2018) SciTS Meritorious Contribution Award (best poster) at the Science of Team Science (SciTS) 2018 Conference, Galveston, TX
- Hazen, RM (2016) Roebling Medal of the Mineralogical Society of America
- Hazen, R.M. (2017) Elected Honorary Member of the Russian Mineralogical Society (one of 13 Americans so honored in the past 200 years) for “the new mineralogy.”

Training	Total # during project period
Undergraduate students	17
Graduate students	15
Post-doctoral fellows	9
Total	41

If you wish you may submit 2 photos related to the project, including new facilities or labs, and equipment



A bipartite network graph of carbon minerals (colored circles) and their localities (black circles). The sizes of circles represent abundances; the colors of mineral circles indicate age of earliest known occurrences; lines between circles indicate co-occurrences. This network reveals unexpected topology related to the large numbers of rare minerals, as well as an embedded time line. (See: Morison et al., *American Mineralogist*, v.102, 1588 (2017).

ADDITIONAL FUNDING: *(Did the project attract additional funding during or beyond the period of the original grant? Please explain and provide a list of all sources of support: government, corporate, foundations, individuals, earned revenues, etc.)*

Funder	Date Awarded	Amount	Purpose of Award
Templeton Foundation	Jan. 2017	\$400,000	Mineral data and origins of life
9 funders	June 2018	\$250,000	4D Workshop
Sloan Foundation	June 2015	~\$2,000,000	Data-driven discovery; carbon science
Hazen Foundation	Jan. 2015	\$350,000	Data-driven discovery; mineralogy

Additional funding from NASA (Mars Science Laboratory) aided in database development.

UNANTICIPATED DEVELOPMENTS OR CHALLENGES/LESSONS LEARNED:

(Describe any factors that have contributed to or impeded the success of the project and explain their affect on the proposed goals and timeline, including funding issues. In hindsight, would you have changed the design of the grant, goals, timeline, personnel, and if so, how?)

We entered this adventurous project confident that new ideas would emerge, but we could not have predicted many advances:

- 1) The recognition that network analysis could be a major tool in analyzing deep-time data, especially paleobiology and mineralogy data. The paleobiology work led to the recognition of a previously unknown mass extinction event in the Ediacaran Period, ~550 million years ago, as well as new insights regarding the ecological impact of subsequent mass extinctions. Applications of network analysis to mineralogy showed network topologies previously unknown that point to deeply embedded patterns in the diversity and distribution of minerals through deep time. Perhaps

the most exciting discovery, still being explored, is the recognition that networks of natural evolving systems embed timelines and other features that have heretofore been hidden.

- 2) Advances in the field that has become known as “mineral ecology” have resulted from application of our large and growing mineral databases to the prediction and discovery of Earth’s “missing minerals”—species that occur on Earth but have yet to be discovered and described. Our detailed predictions of missing carbon-bearing minerals has led to the international Carbon Mineral Challenge, which has led to discovery of at least 17 new carbon minerals (see: mineralchallenge.net).
- 3) Perhaps most importantly, we have galvanized an international community of more than 100 scholars, many of them early career Earth, space, life, and data scientists, who are committed to seeing this field advance. We have held a successful workshop, produced a white paper, and are now actively seeking major funding for an international program.

Given this success, much of it unanticipated but emerging inexorably from the collective effort, I doubt that we would have, in retrospect, changed the design of the program significantly.

KECK PROJECT “CV”

Abstract #1: Morrison et al. (2017)

American Mineralogist, Volume 102, pages 1588–1596, 2017

OUTLOOKS IN EARTH AND PLANETARY MATERIALS Network analysis of mineralogical systems^{4f}

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ABSTRACT

A fundamental goal of mineralogy and petrology is the deep understanding of mineral phase relationships and the consequent spatial and temporal patterns of mineral coexistence in rocks, ore bodies, sediments, meteorites, and other natural polycrystalline materials. The multi-dimensional chemical complexity of such mineral assemblages has traditionally led to experimental and theoretical consideration of 2-, 3-, or n -component systems that represent simplified approximations of natural systems. Network analysis provides a dynamic, quantitative, and predictive visualization framework for employing “big data” to explore complex and otherwise hidden higher-dimensional patterns of diversity and distribution in such mineral systems. We introduce and explore applications of mineral network analysis, in which mineral species are represented by nodes, while coexistence of minerals is indicated by lines between nodes. This approach provides a dynamic visualization platform for higher-dimensional analysis of phase relationships, because topologies of equilibrium phase assemblages and pathways of mineral reaction series are embedded within the networks. Mineral networks also facilitate quantitative comparison of lithologies from different planets and moons, the analysis of coexistence patterns simultaneously among hundreds of mineral species and their localities, the exploration of varied paragenetic modes of mineral groups, and investigation of changing patterns of mineral occurrence through deep time. Mineral network analysis, furthermore, represents an effective visual approach to teaching and learning in mineralogy and petrology.

Keywords: Network analysis, igneous petrology, mineral evolution, copper, chromium, phase equilibria, Bowen’s reaction series, visualization, big data, cluster analysis, multi-dimensional scaling, education

Quantifying ecological impacts of mass extinctions with network analysis of fossil communities

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Contributed by Andrew H. Knoll, March 20, 2018 (sent for review November 15, 2017; reviewed by Mary L. Droser and Seth Finnegan)

Mass extinctions documented by the fossil record provide critical benchmarks for assessing changes through time in biodiversity and ecology. Efforts to compare biotic crises of the past and present, however, encounter difficulty because taxonomic and ecological changes are decoupled, and although various metrics exist for describing taxonomic turnover, no methods have yet been proposed to quantify the ecological impacts of extinction events. To address this issue, we apply a network-based approach to exploring the evolution of marine animal communities over the Phanerozoic Eon. Network analysis of fossil co-occurrence data enables us to identify nonrandom associations of interrelated paleocommunities. These associations, or evolutionary paleocommunities, dominated total diversity during successive intervals of relative community stasis. Community turnover occurred largely during mass extinctions and radiations, when ecological reorganization resulted in the decline of one association and the rise of another. Altogether, we identify five evolutionary paleocommunities at the generic and familial levels in addition to three ordinal associations that correspond to Sepkoski's Cambrian, Paleozoic, and Modern evolutionary faunas. In this context, we quantify magnitudes of ecological change by measuring shifts in the representation of evolutionary paleocommunities over geologic time. Our work shows that the Great Ordovician Biodiversification Event had the largest effect on ecology, followed in descending order by the Permian–Triassic, Cretaceous–Paleogene, Devonian, and Triassic–Jurassic mass extinctions. Despite its taxonomic severity, the Ordovician extinction did not strongly affect co-occurrences of taxa, affirming its limited ecological impact. Network paleoecology offers promising approaches to exploring ecological consequences of extinctions and radiations.

Publications:

2018

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- Moore, E.K., Hao, J., Prabhu A, Zhong H, Jelen, B.I., Meyer, M., Hazen, R.M., and Falkowski, P.G. (2017) Geological and chemical factors that impacted the biological utilization of cobalt in the Archean Eon, *Journal of Geophysical Research: Biogeosciences*, 123, 743–759. <https://doi.org/10.1002/2017JG004067>
- Muscenti, A.D., A. Prabhu, H. Zhong, A. Eleish, M. Meyer, P. Fox, R. Hazen, and A.H. Knoll (2018) Quantifying ecological impacts of mass extinctions with network analysis of fossil communities. *Proceedings of National Academy of Sciences* Apr 2018, 201719976; DOI: 10.1073/pnas.1719976115.
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- Wang, C., Ma, X., Chen, J., Chen, J. (2018) Information extraction and knowledge graph construction from geoscience literature. *Computers & Geosciences*, 112, 112-120. <https://doi.org/10.1016/j.cageo.2017.12.007>
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- Hazen, R.M. (2017) Acceptance of the 2016 Roebling Medal of the Mineralogical Society of America. *American Mineralogist*, **102**, 1134-1135.
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- Morrison, S. M., Liu, C., Eleish, A., Prabhu, A., Lic, C., Ralph, J., Downs, R. T., Golden, J. J., Fox, P., and Hazen, R. M. (2017) Network Analysis of Mineralogical Systems, *American Mineralogist*, 102, 1588-1596.
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- Knoll, A.H. and M.J. Follows (2016) A bottom-up perspective on ecosystem change in Mesozoic oceans. *Proceedings B, Royal Society*, 20161755, doi/10.1098/rspb.2016.1755.
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- Liu, X.-M., Kah, L.C., Knoll, A.H., Cui, H., Kaufman, A.J., Shahar, A., and Hazen, R.M. (2015) Tracing Earth's CO₂ evolution using Zn/Fe ratios in marine carbonate. *Geochemical Perspectives Letters*, 2: 24-34.

Papers in Review/Revision:

- Hazen, R.M. (2018) A new system of mineralogy: Proposal for a classification based on natural kind clustering. *American Mineralogist*, in review.
- Hazen, R.M., Downs, R.T., Elesish, A., Fox, P., Gagné, O., Golden, J.J., Grew, E.S., Hummer, D.R., Hystad, G., Krivovichev, S.V., Li, C., Liu, C., Ma, X., Morrison, S.M., Pan, F., Pires, A.J., Prabhu, A., Ralph, J., Runyon, S.E., and Zhong, H. (2018) Data-driven discovery in mineralogy: Recent advances in data resources, analysis, and visualization. *China Engineering*, in review.
- Hazen, R.M. (2018) Earth in five reactions: Grappling with meaning and value in science. *American Mineralogist*, in review.
- Cantine, M., K. Bergmann, and A.H. Knoll (2018) Carbonates before skeletons: a database approach. *Earth Science Reviews*, in prep. (should be submitted by August)
- Estrada, C., Sverjensky, D.A., and Hazen, R.M. (2017) Selective adsorption of calcium-aspartate ligands onto [Mg(OH)₂]-brucite: Implications for calcium in prebiotic chemistry. *Astrobiology*, in press.
- Fornaro, T., Hazen, R.M., Boosman, A., Brucato, J., Loes ten Kate, I., Siljeström, S., Poggiali, and Steele, A. (2018) "UV irradiation of biomarkers adsorbed on minerals under Martian-like conditions: Hints for life detection on Mars. *Icarus*, in review.
- Hao, J., Sverjensky, D.A., and Hazen, R.M. Importance of Atmospheric H₂ in Surficial Environments of the Archean, *Geobiology*, submitted.
- Hao, J., Sverjensky, D.A., and Hazen, R.M., Limits on the partial pressure of H₂ in the Archean atmosphere during weathering of basaltic minerals. *Geochimica et Cosmochimica Acta*, in review.
- Hummer DR, Golden JJ, Hystad G, Downs RT, Eleish A, Liu C, Ralph J, Morrison SM, Meyer MB, and Hazen RM (2018) The oxidation of Earth's crust: Evidence from the evolution of manganese minerals, *Nature Communications* (In Revision)
- Hystad G, Eleish A, Downs RT, Morrison SM, and Hazen RM (2018) Bayesian estimation of Earth's undiscovered mineralogical diversity, *Mathematical Geosciences* (In Review)
- Ma, X., Madhikarmi, B.L., Hummer, D., Golden, J.J., Fox, P.A., Hazen, R.M., Morrison, S.M., Downs, R.T., Meyer, M.B., A Three-Dimensional Heat Map Matrix for Showing Co-relationships in Network Analysis. In Preparation.
- Muscente, A.D., N. Bykova, T.H. Boag, L.A. Buatois, A. Eleish, A. Prabhu, M.B. Meyer, J.D. Schiffbauer, P. Fox, R.M. Hazen, and A.H. Knoll (2018) Network analysis reveals ecological community reorganization prior to the Ediacaran-Cambrian transition. MS in prep. (To be submitted in September to *Nature Communications*)
- Muscente, A.D., Morrison, S.M., Eleish, A., Prabhu, A., Zhong, H., Liu, C., Golden, J.J., Hummer, D.R., Meyer, M.B., Fox, P., Downs, R.T., Falkowski, P., Knoll, A.H., Hazen, R.M. (2018) Studying Earth system history with network analysis. MS in prep. (To be submitted to *Geobiology* in September)

Books:

- Hazen, R.M., 2019, *Symphony in C: Carbon and the Emergence of (Almost) Everything*. New York: Norton, in press.
- Ma, X., 2018. Data Science for Geoscience: Leveraging Mathematical Geosciences with Semantics and Open Data. *Handbook of Mathematical Geosciences: Fifty Years of IAMG*. Springer. 16pp. 687-702.
- Ma, X., 2018. Spatial Data. In: Schintler, L.A., McNeely, C.L. (eds.) *Encyclopedia of Big Data*. Springer, Cham, Switzerland. http://dx.doi.org/10.1007/978-3-319-32001-4_192-1
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- Prabhu, A. (2017) Informatics. In: Schintler, L.A., McNeely, C.L. (eds.) Encyclopedia of Big Data. Springer, Cham, Switzerland. In review.
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Meeting abstracts/Presentations:

2018

- Prabhu, A (Invited) Data Science for Geoscience Workshop, Goldschmidt Conference, Boston, MA (2018). “Visualization.”
- Prabhu, A (Invited) Guest Lecture, Readings in Semantic Web, Rensselaer Polytechnic Institute, Troy, NY (2018). “Data Visualization.”
- Knoll, A (2018) Plenary Lecture, 5th International Paleontological Congress, Paris, France 2018
- Knoll, A (2018) Sven Berggren Lecture, Royal Physiographic Society, Lund, Sweden 2018
- Hao, J., Huang, F., Sverjensky, D.A., Hazen, R.M., Daniel, I. (2018) Late Archean weathering of phosphorus: implications for Earth’s early P cycle, *4-D workshop*, Washington, DC
- Hao, J (2018) Geochemistry of trace elements: co-evolution of geosphere and biosphere, China University of Geosciences, Wuhan, China
- Hao, J (2018) Mineral, water, biomolecules: how to make life? University of Science and Technology of China, Hefei, China
- Hazen RM, Hystad G, Downs RT, Eleish A, Morrison SM (2018) A revised (upwards) estimate of Earth’s “missing” minerals, IMA
- Ma, X., Fox, P., Hazen, R., Hummer, D., Golden, J., Downs, R., Hystad, G., Muscente, A.D., 2018. A Justification on the Need to Build a Machine-Readable Knowledge Base of Deep Time. The 4D Workshop: Deep-time Data Driven Discovery and the Evolution of Earth, Washington, DC, USA. Poster Presentation.
- Morrison S.M. “Coevolution of minerals and the biosphere in a big data framework” Deep Carbon Cycle (DCC) Workshop, Cambridge, UK (April 2018)
- Morrison SM, Eleish A, Prabhu A, Fox P, Ralph J, Golden JJ, Downs RT, Liu C, Runyon SE, and Hazen RM (2018) Characterizing carbon mineralogy through Earth history with data-driven techniques, Deep Carbon GRC
- Morrison SM, Eleish A, Prabhu A, Fox P, Ralph J, Golden JJ, Downs RT, Liu C, Runyon SE, and Hazen RM (2017) Characterizing carbon mineralogy through Earth history with data-driven techniques, EGU
- Morrison SM, Prabhu A, Eleish A, Pan F, Fox P, Ralph J, Golden JJ, Downs RT, Liu C, Runyon SE, and Hazen RM (2018) Recent advances in mineral evolution and ecology via big data analytics and visualization, IMA
- Morrison, S.M. “Transition element availability through deep time” (Invited) Earth-Life Science Institute (ELSI), 6th ELSI Symposium: Building Bridges from Earth to Life, Tokyo, Japan, (January 9, 2018)

2017

- Fox P, Eleish A, Li C, Pan F, Prabhu A, Zhong H, and DTDI Team (2017) Heterogeneity and Heterarchy: How far can network analyses in Earth and space sciences? (Invited), AGU, Abstract #212818. (December, 2017)
- Golden, J.J. Overview of Mineral Evolution, Mineral Ecology, and the Mineral Evolution Database, Society of Earth Science Students, University of Arizona (October 6, 2017)
- Hao, J (2017) Geochemical environments of the Earth and other habitable planets: implications for the origin of life, Louisiana State University, Baton Rouge, LA
- Hazen RM (Invited), Eleish A, Liu C, Morrison SM, Meyer M, and Keck DTDI Consortium (2017) Network Analysis of Earth’s Co-Evolving Geosphere and Biosphere, AGU, Abstract # PP43E-01 (December, 2017)
- Hazen, R.M. (Invited) Mineral Ecology and Mineral Evolution in the Era of «Big Data», 200th Anniversary Meeting of the Russian Mineralogical Society (October 2017)
- Hazen, R.M. Carbon mineral network analysis: A big data geobiology study. Goldschmidt Conference, Paris, France. (August 15, 2017)
- Hazen, R.M. Chance, necessity and the origins of life. Fundamentals of Life in the Universe Symposium, Groningen, The Netherlands.
- Hazen, R.M. Deep-Time Evolution of Rocks and Life. Covington Law Office, Washington DC. (May 8, 2017)
- Hazen, R.M. Mineral evolution in the era of big-data mineralogy. Austrian Academy of Sciences, Vienna. (April 5, 2017)
- Hazen, R.M. Minerals and the origins of life: Insights from big data mineralogy. Astrobiology Science Conference 2017, Mesa, Arizona. (April 24, 2017)
- Hazen, R.M. Minerals and the origins of life. ISSOL Conference, La Jolla, California. (July 18, 2017)

- Hazen, R.M. Network analysis applications to carbon mineral systems. Deep Carbon Observatory Science Meeting, St. Andrews, Scotland. (March 25, 2017)
- Hazen, R.M. Precambrian paleomineralogy: The known, unknown, and unknowable Goldschmidt Conference, Paris, France. (August 18, 2017)
- Hazen, R.M. Private lives of minerals: network analysis of rocks and minerals. Syracuse University, Chauncey Holmes Lecture.
- Hazen, R.M. The evolution of mineral evolution. Vienna Museum of Natural History, opening keynote address of the mineral evolution exhibit. (April 4, 2017)
- Hummer DR, Golden JJ, Hystad G, Downs RT, Eleish A, Liu C, Ralph J, Morrison SM, Meyer MB, Hazen RM (2017) Timing the oxidation of Earth's crust: Evidence from big data records of manganese mineralization, AGU, Abstract #V24C-03 (December, 2017)
- Hummer, D.R. Ecology and evolution of manganese minerals: Implications for the redox history of Earth and life. D. Hummer, lead presenter. Goldschmidt Conference, Paris, France. (August 15, 2017)
- Hummer, D.R. The Carbon Mineral Challenge: A worldwide search for undiscovered minerals. Deep Carbon Observatory Science Meeting, St. Andrews, Scotland. (March 25, 2017)
- Hystad, G. Estimation of the total number of mineral species on Earth and the characterization of Earth-like planets. (Talk, Women in Statistics and Data Science Conference, 2017)
- Knoll, A.H. Invited lecture, Danish Museum of Natural History, Copenhagen (21 June 2017)
- Knoll, A.H. Teacher, workshop on physiology and Earth system evolution. University of Erlangen Germany (1 August 2017)
- Knoll, A.H., Leeuwenhoek Lecture, University of Leiden, Netherlands (18 May 2017)
- Liu, C. What's up with Rodinia. [PetroChina Company Limited](#), Beijing. (August 22, 2017)
- Liu, C., A.H. Knoll, and R.M. Hazen (2017) What's up with Rodinia? (GSA, 2017)
- Ma, X. [Invited], Fox, P., Kolankowski, S., Hummer, D., Hazen, R.M., Golden, J.J., Meyer, M., 2017. Leveraging Data Science for Geoscience: Experience from the Deep Time Data Infrastructure. (AbSciCon2017)
- Ma, X. Doing geoinformatics with a web of data. (GSA, 2017)
- Meyer, M.B. Deep-time Data Infrastructure: Visualizing the Co-Evolution of Planets and Life. Astrobiology Science Conference 2017, Mesa, Arizona. (April 25, 2017)
- Moore E, Jelen B, Giovannelli D, Prabhu A, Raanan H, and Falkowski P (2017) The Importance of Transition Metals in the Expanding Network of Microbial Metabolism in the Archean Eon, AGU, Abstract #281932. (December, 2017)
- Morrison SM, Eleish A, Runyon SE, Prabhu A, Fox P, Ralph J, Golden JJ, Downs RT, Liu C, Meyer MB, and Hazen RM (2017) Data-driven exploration of copper mineralogy and its application to Earth's near-surface oxidation, AGU, Abstract #PP41B-1306 (December, 2017)
- Morrison SM, Eleish A, Runyon SE, Prabhu A, Fox P, Ralph J, Golden JJ, Downs RT, Liu C, Meyer MB, and Hazen RM (2017) Copper mineral ecology and evolution, 200th Anniversary Meeting of the Russian Mineralogical Society (October 2017)
- Morrison, S.M. Copper mineral ecology and network analysis through deep time. S.M. Morrison, R.M. Hazen, et al. Deep Carbon Observatory Science Meeting, St. Andrews, Scotland. (March 25, 2017)
- Morrison, S.M. Mineral network analysis applications in comparative planetology. Astrobiology Science Conference 2017, Mesa, Arizona. (April 24, 2017)
- Morrison, S.M. Network analysis applications: Exploring geosphere and biosphere co-evolution with big data techniques. Goldschmidt Conference, Paris, France. (August 15, 2017)
- Morrison, S.M., Eleish, A., and Hummer, D.R. Network analysis applications to carbon mineral systems. (Invited) Deep Carbon Observatory Science Meeting, St. Andrews, Scotland. (March 23, 2017)
- Muscente, A.D., N. Bykova, T.H. Boag, L. Buatois, A. Eleish, A. Prabhu, M. Meyer, J.D. Schiffbauer, P. Fox, R. Hazen, and A.H. Knoll (2017) Ediacaran macrofossil assemblages and biozones in light of network theory. Abstracts, International Symposium on the Ediacaran-Cambrian Transition, St. John's, Newfoundland, p. 84.
- Muscente, A.D., N. Bykova, T.H. Boag, L.A. Buatois, A. Eleish, M. Meyer, J.D. Schiffbauer, P. Fox, R.M. Hazen, and A.H. Knoll. Network analysis of fossil co-occurrence in the Ediacaran and Paleozoic. (GSA, 2017)
- Ostroverkhova A, Prabhu A, Golden JJ, Hazen RM, Downs RT, Morrison SM (2017) Минеральная эволюция лития (Mineral evolution of lithium), 200th Anniversary Meeting of the Russian Mineralogical Society (October 2017)
- Prabhu A, Fox P, Zhong H, Eleish A, Ma X, Zednik S, Morrison SM, Moore E, Muscente D, Meyer M, Hazen RM, and The Deep Time Data Infrastructure Team (2017) Visualizing Complex Environments in the Geo- and Bio Sciences, AGU, Abstract #259289. (December, 2017)
- Prabhu A. Network Analysis in Earth Science, Web Science Conference, Troy, NY (June 2017)
- Zhong H, Ma X, Prabhu A, Eleish A, Pan F, Parsons M, Ghiorso M, West P, Zednik S, Chen Y, Wang H and Fox P (2017) Thermodynamic Data Rescue and Informatics for Deep Carbon Science, AGU, Abstract #242908. (December, 2017)

2016

- Downs, R.T. Determination of valence states for the minerals (Talk, GSA 2016)
- Falkowski, P. The co-evolution of minerals and life (Talk, GSA 2016)
- Golden, J.J. Building the Mineral Evolution Database: Implications for future big data analysis (Poster, GSA 2016)
- Grew, E. Counting boron minerals in Earth's crust: Can contradictory evidence be reconciled? (Talk, GSA 2016)
- Hao, J., Sverjensky, D. A., Hazen, R. M., Weathering and Late Archean World Average River Water, Goldschmidt 2016 (June 29th, 2016)
- Hao, J., Sverjensky, D.A., and Hazen, R.M., Importance of Atmospheric H₂ in Surficial Environments of the Archean, Second DCO Yellowstone Summer School (2016), Poster

- Hao, J., Sverjensky, D.A., and Hazen, R.M., Weathering and late Archean riverine transport, Australasian Astrobiology Meeting in Perth, Australia, 2016, Presentation.
- Hazen, R.M. Mineral evolution of first-row transition elements. 2nd European Mineralogical Association Conference, Rimini, Italy. (September 12, 2016)
- Hazen, R.M. Mineral evolution. DCO Summer School, Chaco Hot Springs, Montana. (July 26, 2016)
- Hazen, R.M. MSA Roebling Medal Lecture: The co-evolution of Earth and life; insights from 'Big Data' mineralogy (Talk, GSA 2016)
- Hazen, R.M. On the mineralogy of the Anthropocene Epoch. 2nd European Mineralogical Association Conference, Rimini, Italy. (September 12, 2016)
- Hazen, R.M. Private lives of minerals: Social network analysis applied to mineralogy and petrology. (Talk, AGU 2016)
- Hazen, R.M. The origins of life. DCO Summer School, Chaco Hot Springs, Montana. (July 28, 2016)
- Hazen, R.M. The Private Lives of Minerals, Neighborhood Lecture, Carnegie Inst. for Science, Geophysical Laboratory, November, 2016
- Hazen, R.M., Chance vs. Necessity in Earth's Mineral Evolution; Philosophical Society of Washington, Washington DC. (Feb. 19, 2016)
- Hazen, R.M., Chance, necessity, and the origin of life; International Astrobiology Conference, Vilnius, Lithuania. (April 26, 2016)
- Hazen, R.M., Chance, necessity, and the origins of life; Calvert Marine Museum, Solomons, MD. (April 9, 2016)
- Hazen, R.M., Chance, necessity, and the origins of life; Philosophy of Biology seminar, Sorbonne, Paris, France. (March 9, 2016)
- Hazen, R.M., Chance, necessity, and the origins of life; The Morgan Lecture, Appalachian State University, Boone, NC. (March 23, 2016)
- Hazen, R.M., Chance, necessity, and the origins of life. Argonne National Laboratory, Argonne, IL, (October 18, 2016)
- Hazen, R.M., Coevolution of the geosphere and biosphere: Insights from deep-time data. Keck Foundation, Los Angeles, CA, (November 30, 2016)
- Hazen, R.M., Mineral ecology and evolution of first-row transition elements. Goldschmidt Conference, Yokohama, Japan (June 30, 2016)
- Hazen, R.M., Mineral ecology: Chance and necessity in the evolution of terrestrial planets; Institute de Physique du Globe de Paris, France. (March 10, 2016)
- Hazen, R.M., Mineral evolution, mineral ecology, and the coevolution of the geosphere and biosphere; Geology Department Seminar, Appalachian State University, Boone, NC. (March 23, 2016)
- Hazen, R.M., On the mineralogy of the Anthropocene Epoch. Goldschmidt Conference, Yokohama, Japan (July 1, 2016)
- Hazen, R.M., Private lives of minerals. Carnegie Institution for Science, Washington, DC, (November 15, 2016)
- Hummer, D.; Hazen, R.M.; Ma, X.; Golden, J.J.; Downs, R.T. Constraints on the mineral evolution of planetary crusts using statistical correlations and anti-correlations among the mineral-forming elements. Goldschmidt Programs and Abstracts, session 6f, June 2016.
- Hummer, D.R. Quantifying and visualizing earth's mineral chemistry through geologic time (Talk, GSA 2016)
- Hystad, G. Prediction of Earth's "Missing" Minerals and the Relative Abundances of Mineral Species on Earth: A Statistical Measure to Characterize Earth-like Planets (Talk, GSA 2016)
- Hystad, G., Downs, R.T., Hazen, R.M., Mineral species frequency distribution and the prediction of Earth's missing minerals, JSM 2016 (August 1st, 2016)
- Jelen, B., Giovannelli, D., Vetriani, C., The Sulfur Reduction Pathway in *T. ammonificans*, a deep sea vent bacterium from the phylum Aquifex, Northeast Geobiology Symposium at Harvard. (April 2016)
- Knoll, A. H., The Proterozoic Eon: Earth and Life at Middle Age, Geobiology Workshop, University of Tübingen, Germany. June 1, 2016.
- Knoll, A.H. Invited lecture, Max Planck Institute for Genetics and Cell Biology, Dresden, Germany (6 October 2016)
- Knoll, A.H. Plenary lecture, Swiss geoscience meeting, Geneva, Switzerland (19 November 2016)
- Knoll, A.H. Public lecture, Colegio Nacional, Mexico City (20 October 2016)
- Kolankowski, S. DTDI Poster: Deep Time Data Infrastructure: Integrating Our Current Geologic Databases (Poster, GSA 2016)
- Kolankowski, S. DTDI Poster: Deep Time Data Infrastructure: Integrating Our Current Geologic Databases (Poster, AGU 2016)
- Krivovichev, S.V. Structural and chemical complexity of minerals: relations and time evolution. 2nd European Mineralogical Association Conference, Rimini, Italy. (September 13, 2016)
- Liu, C. Chromium and Vanadium Mineral Ecology (Talk, GSA 2016)
- Liu, C. Lithium adsorption onto mineral surfaces of kaolinite, gibbsite, goethite, and hematite; Goldschmidt Conference, Yokohama, Japan. (June 29, 2016)
- Liu, C.: Reconstructing the evolution of first-row transition metal minerals by GeoDeepDive, (Poster, AGU 2016)
- Ma, X.: Showing co-relationships between elements and minerals in a three-dimensional matrix (Poster w/ laptop; GSA 2016)
- Meyer, M.B. Co-evolution of the Geo- and Biospheres: An integrated program for data-driven, abductive discovery in the Earth sciences (Poster, GSA 2016)
- Meyer, M.B. Insights into Vendotaenid taphonomy and structure: New data on an old fossil (Talk, GSA 2016)
- Meyer, M.B., Estimating oxygen availability and gas exchange in a fossil microbial mat using computed tomography X-ray imaging: Implications for life-sediment interactions and early trace maker metabolisms in the late Ediacaran of South China, Northeast Geobiology Symposium at Harvard. (April 2016)

- Moore, E. K., Global Redox Influence on Metal Availability and the Emergence of Archean Metabolisms, Northeast Geobiology Symposium at Harvard. (April 2016)
- Morrison, S.M. Exploiting mineral data: applications to the diversity, distribution, and social networks of copper mineral, (Poster, AGU 2016)
- Morrison, S.M. Mineral ecology: Social network analysis and sociograms of mineral connections, distributions, and segmentation. (Talk, GSA 2016)
- Morrison, S.M. Social network of copper minerals: a mineral ecology study (Talk, Session T129)/ Mineral Ecology: Social network analysis and sociograms of mineral connections, distributions, and segmentation (Poster, GSA 2016)
- Muscente, A. D., Broce, J., Gill, B., Xiao, S., Authigenic and early diagenetic minerals as indicators of geomicrobiological processes in shelly fossil preservation and their significance for late Neoproterozoic-early Palaeozoic near-surface environments, Northeast Geobiology Symposium at Harvard. (April 2016)
- Muscente, A.D. Exceptionally preserved fossil assemblages through geologic time and space (Talk, GSA 2016)

Conference Sessions:

- AGU 2017 IN33B (oral) and IN31E (poster): Linked Data in the Earth Sciences. Conveners: Prabhu A., Morrison S.M., Ma X., Lehnert K., Klump J.F.
- Goldschmidt 2017 14A (oral and poster): Exogenous Organic Compounds, Minerals, Prebiotic Molecules and Geobiotropy. Conveners: Morrison S.M., Hummer D.R., Bassez M.P., Holm N., Remusat L., Martins Z.
- GSA 2016 T129 (oral and poster): Mineralogical Evidence for the Co-Evolution of the Geosphere and Biosphere: In Honor of Robert M. Hazen, 2016 Roebling Medalist. Conveners: Grew E.S., Ross N.L., Hummer D.R.

Synergistic Activities:

2018

- Ma, X., 2018. Data Science for Complex Systems: Cross-Disciplinary Collaborations from Elements to Ecosystems, Biology of Vector-borne Diseases (BVBD) Summer Course, Moscow, ID.
- Ma, X., 2018. Geo-Data Science: Leveraging Geoscience Research with Geoinformatics, Semantics and Open Data, UI-WSU Geology Seminar, Moscow, ID.
- Online Demo: 3D heat map to show co-relationships between elements and mineral species <http://www2.cs.uidaho.edu/~max/PeriodicTable/PeriodicTable.html>
- Online Demo: Visualization of local geologic time scale of North America and application in data exploration <http://www2.cs.uidaho.edu/~max/gts/>
- Prabhu, A. DCO Webinar Wednesday, Deep Carbon Observatory, Carnegie Institution for Science (2018). "Data Science for Geosciences : Analytics".

2017

- Eleish, A. and Morrison S.M. Deep Carbon Observatory (DCO) Webinar Series: "Visual Tools for Big Data Network Analysis"
- Prabhu A. Deep Carbon Observatory (DCO) Webinar Series: "Making Sense of Jupyter Notebooks"
- Eleish A. Workshop: Applying network analysis to Earth science data. Deep Carbon Observatory Science Meeting, St. Andrews, Scotland. (March 2017)
- Eleish A. Workshop: Applications of Jupyter notebooks. Deep Carbon Observatory Science Meeting, St. Andrews, Scotland. (March 2017)
- Ma, X., 2017. Weaving a Knowledge Network for a Research Program using Semantic Web Technologies. University of Idaho Library Workshop, Moscow, ID.
- Ma, X., Hodson, S., 2017. Open Science, FAIR Data and Data Standards. Workshop for Research Data Management at the 67th Annual Meeting of the American Crystallographic Association, New Orleans, LA.
- Ma, X, University of Idaho Data Science course: ISEM301 The Beauty of Data Science, 1 credit (continuing)
- Ma, X, University of Idaho Data Science course: Data Science course: CS479/579 Data Science, 3 credits (continuing)

Media:

2017

- Press coverage of "On the mineralogy of the Anthropocene Epoch:" ~400 media outlets in 20 languages and 50 countries, with an estimated 600 million reads (March 2017). Media reports include Scientific American, Discover, New Scientist, Chemical and Engineering News, the Canadian Broadcasting System, BBC, Popular Science, and numerous other media outlets.
- Press coverage of "Network Analysis of Mineralogical Systems": ~150 media outlets in 13 languages and 38 countries, with an estimated 250 million reads (August 2017). Media reports include Reuters, BBC, Inside Science, New York Times, and numerous other media outlets.

- Press conference for opening of the mineral evolution exhibit: Vienna Museum of Natural History, press conference presentation. (Hazen, R.M., April 4, 2017)

2016

- Press coverage of “On the nature and significance of rarity in mineralogy.” ~500 media outlets in 25 languages and 50 countries, with an estimated 600 million reads (February 2016).
- Hazen, R.M., “Life’s Rocky Start.” Premiere of a NOVA TV show about Hazen, plus discussion period following. Carnegie Institution for Science, Washington, DC. (Feb 2, 2016)
- Hazen, R.M., “Treasures of the Earth” series, NOVA (WGBH-TV). “Gems” aired on November 2, 2016 and “Power” aired November 16, 2016.

Awards/Honors:

- Knoll, A (2017) Doctor of Science honoris causa, American Museum of Natural History
- Knoll, A (2018) Sven Berggren Prize, Royal Physiographic Society, Sweden
- Knoll, A (2018) GSA Geobiology and Geomicrobiology Division Award
- Ma, X (2018) SciTS Meritorious Contribution Award (best poster) at the Science of Team Science (SciTS) 2018 Conference, Galveston, TX
- Hazen, RM (2016) Roebling Medal of the Mineralogical Society of America
- Hazen, R.M. (2017) Elected Honorary Member of the Russian Mineralogical Society (one of 13 Americans so honored in the past 200 years) for “the new mineralogy.”

Leverage from other grants:

- Xiaogang Ma (PI), Leveraging data science to explore co-relationships between elements and minerals, UI Office of Research and Economic Development (ORED) Seed Grant, \$11,795.57 (2017)
- Robert Hazen (PI), Chance, necessity, and the origins of life. John Templeton Foundation (\$400,000).
- Robert Hazen (PI), The 4D Workshop: Deep-time Data-Driven Discovery. Sloan Foundation (\$125,000); NASA (\$50,000); Carnegie Institution (\$20,000); Moore Foundation (\$20,000); Earth-Life Science Institute, Tokyo (\$20,000); United States Geological Survey (\$8,000); other sources (\$24,500).
- The Robert and Margaret Hazen Foundation, \$300,000.
- NASA, Mars Science Laboratory support for data science (~\$150,000).
- Alfred P. Sloan Foundation, grants to the Carnegie Institution and University of Arizona related to the Deep Carbon Observatory. (~\$2,000,000 devoted to related aspects of data science in 2015-2019).

Additional personnel/collaborators:

Kristin Bergmann (MIT)

Marjorie Cantine (MIT)

Edward Grew (Univ. Maine)

Sergey Krivovichev (St. Petersburg Tech, Russia)

Grethe Hystad (Purdue Univ. NW)