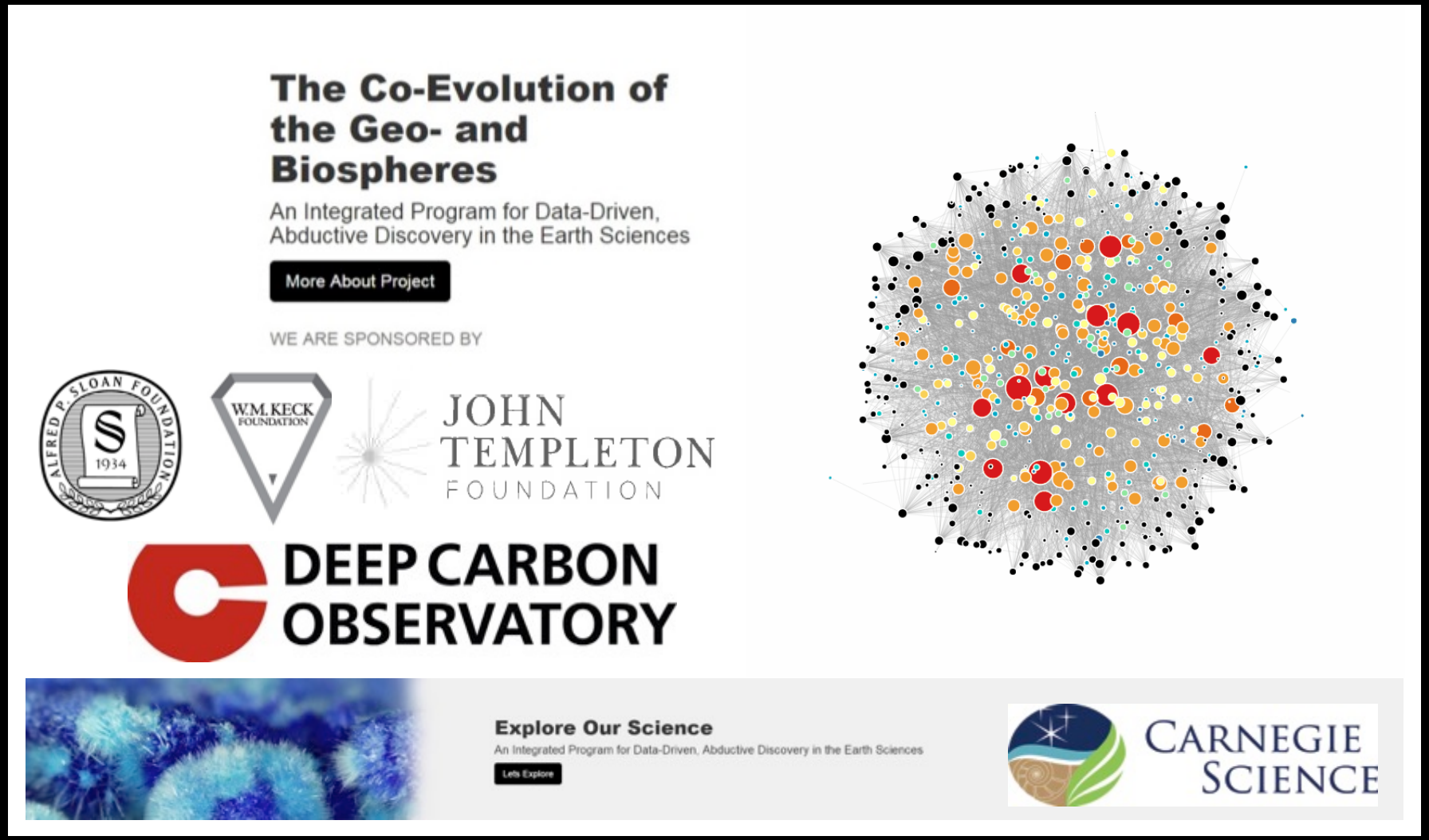
Exploring Complex Mineral Systems and the Co-evolution of Earth Materials with the Biosphere

Shaunna M. Morrison (@s__morrison)

Carnegie Institution for Science

July 10, 2019 | AKTRU2019 Symposium

The Deep-Time Data Infrastructure



Please visit: dtdi.carnegiescience.edu

4D Deep-time Data Driven Discovery

About Committees Archive Participants Resources

ALFRED P. SLOAN FOUNDATION 1934

4D Workshop:

Deep-time Data Driven Discovery and the Evolution of Earth

4-6 June 2018

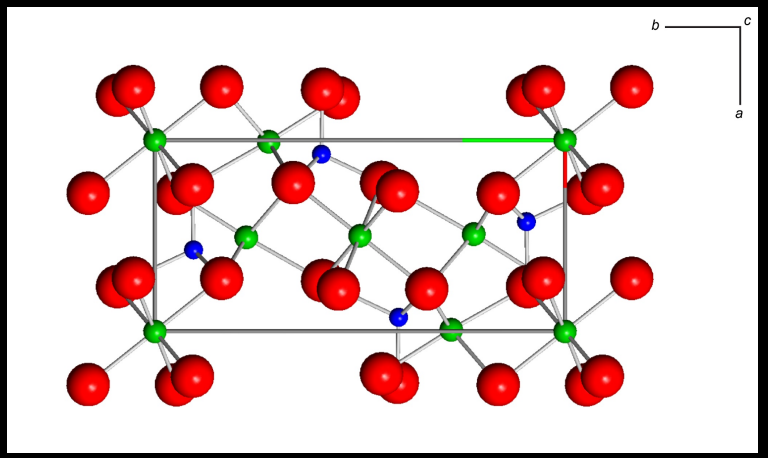
Please visit: 4d-workshop.net

What is a mineral?

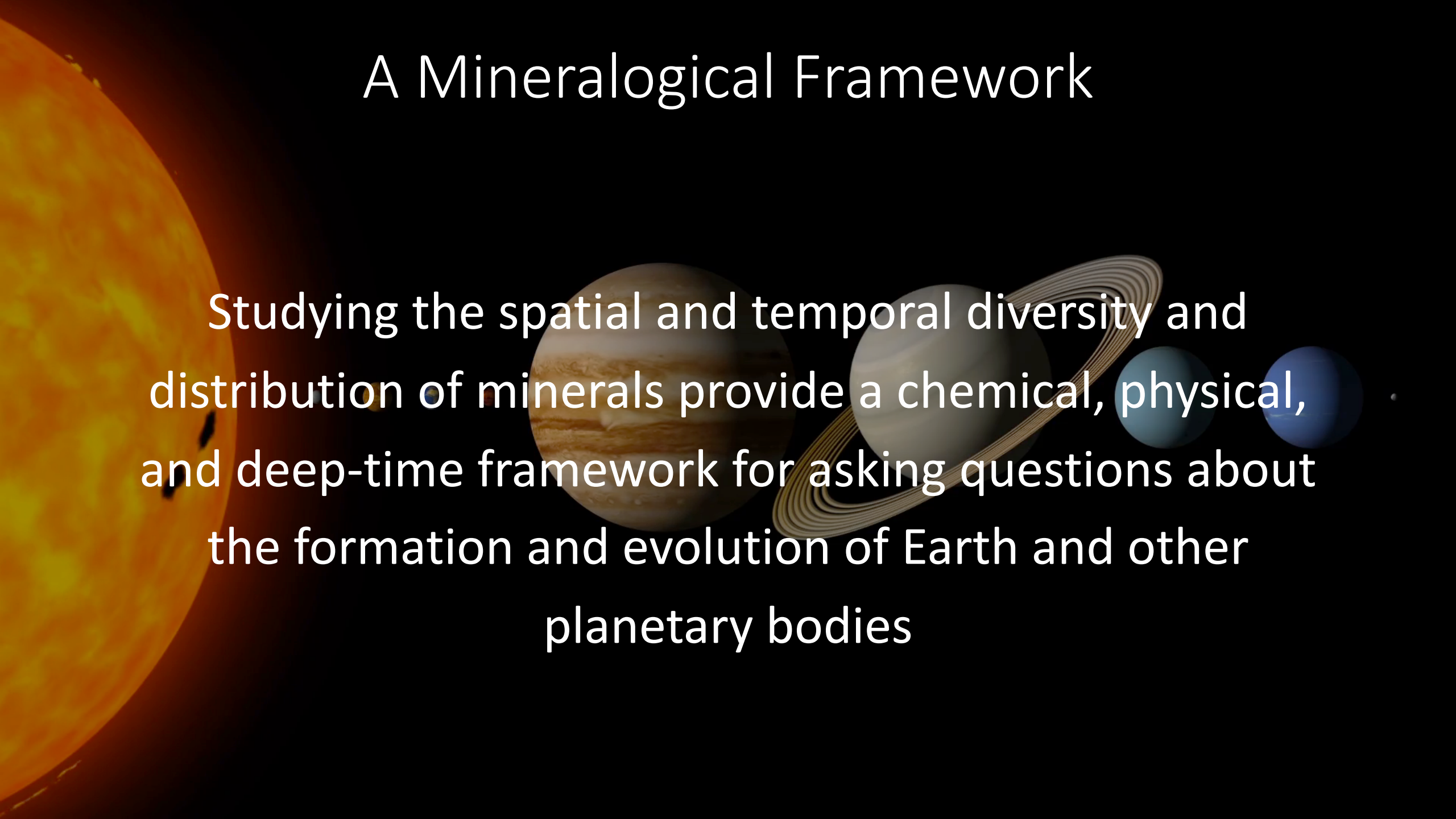
A naturally occurring solid with:

A well-defined composition (Mg_2SiO_4)

A well-defined crystal structure (Pbnm)



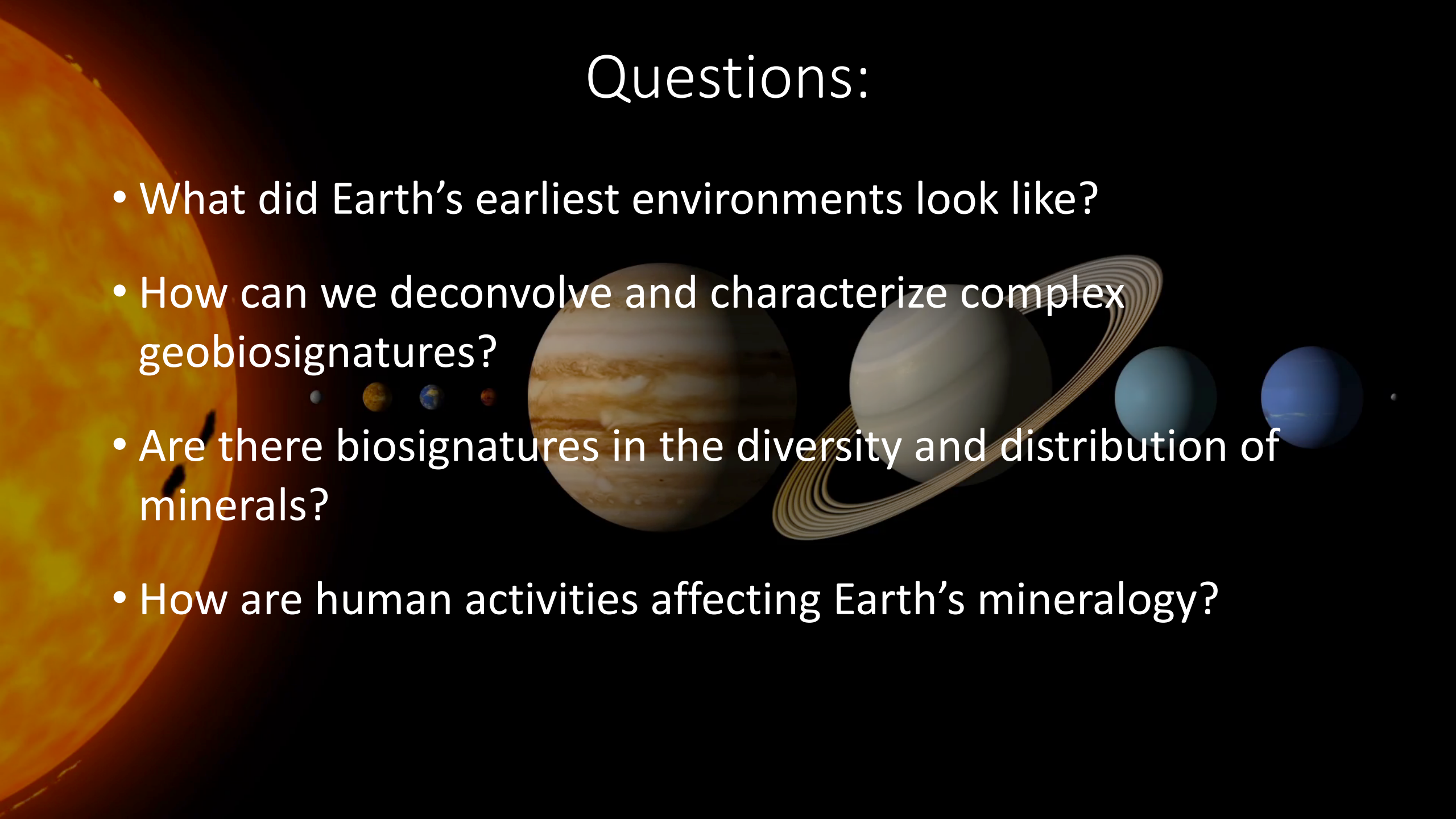
A Mineralogical Framework



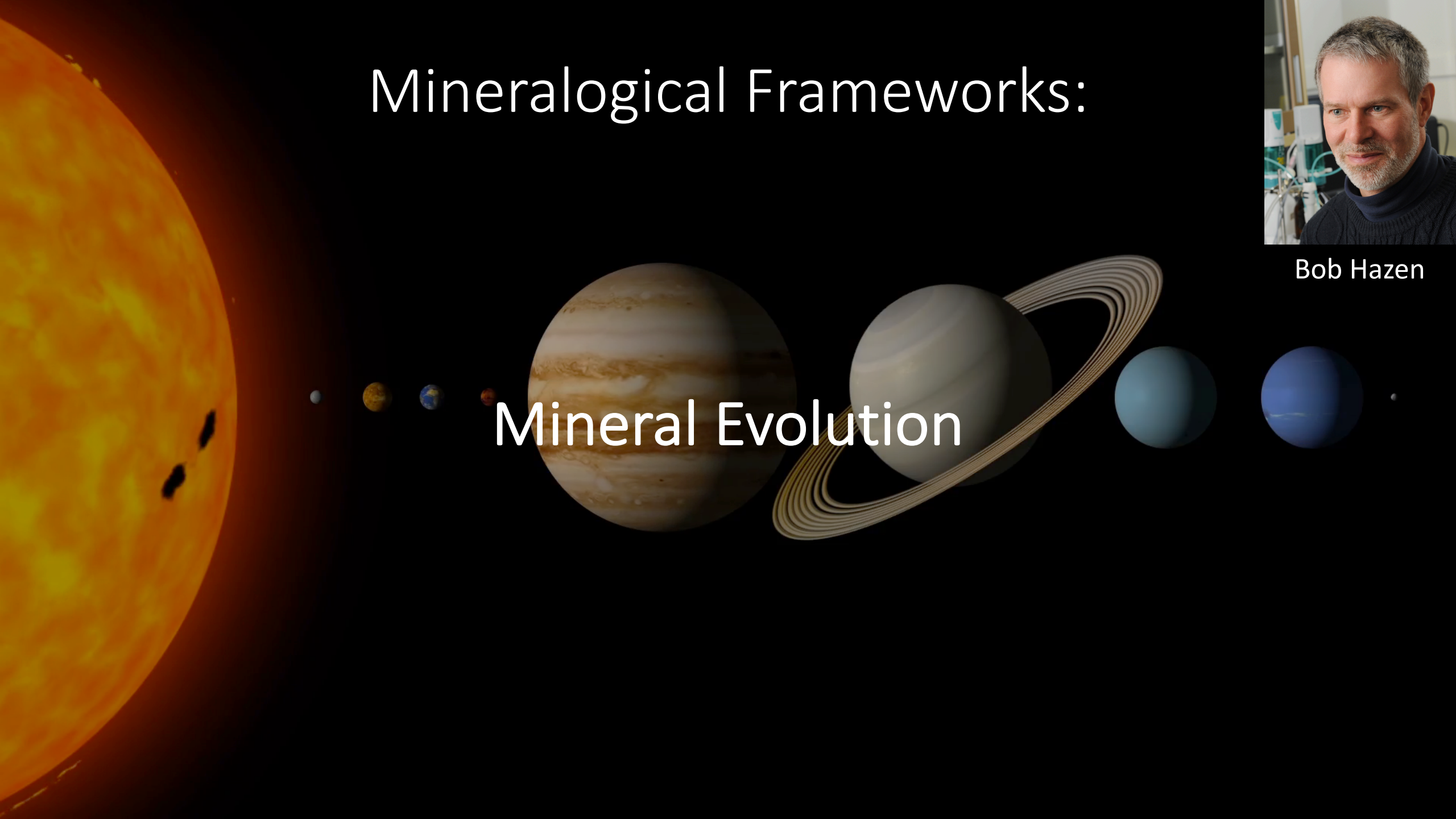
Studying the spatial and temporal diversity and distribution of minerals provide a chemical, physical, and deep-time framework for asking questions about the formation and evolution of Earth and other planetary bodies

Questions:

- What did Earth's earliest environments look like?
- How can we deconvolve and characterize complex geobiosignatures?
- Are there biosignatures in the diversity and distribution of minerals?
- How are human activities affecting Earth's mineralogy?



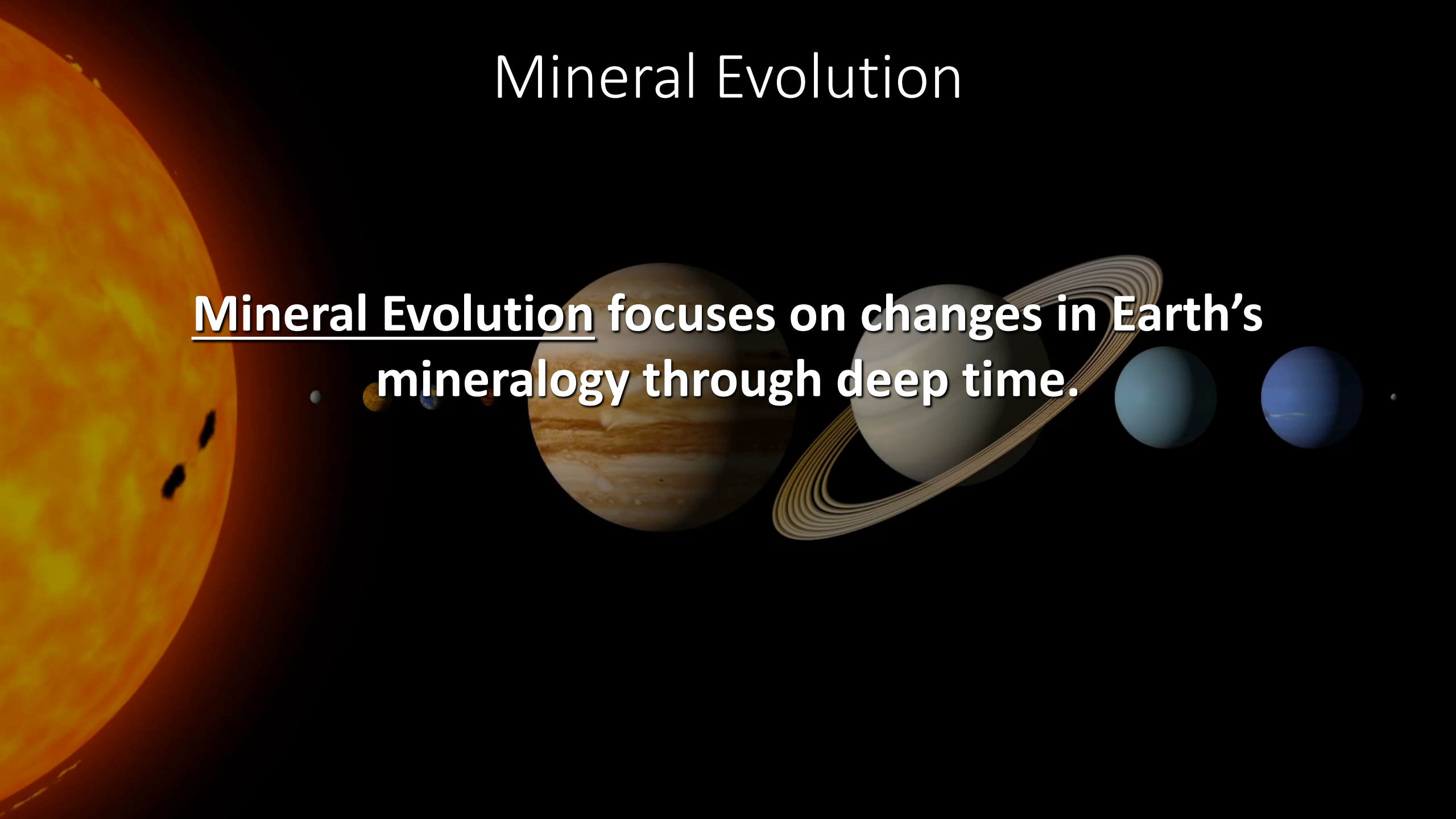
Mineralogical Frameworks:



Bob Hazen

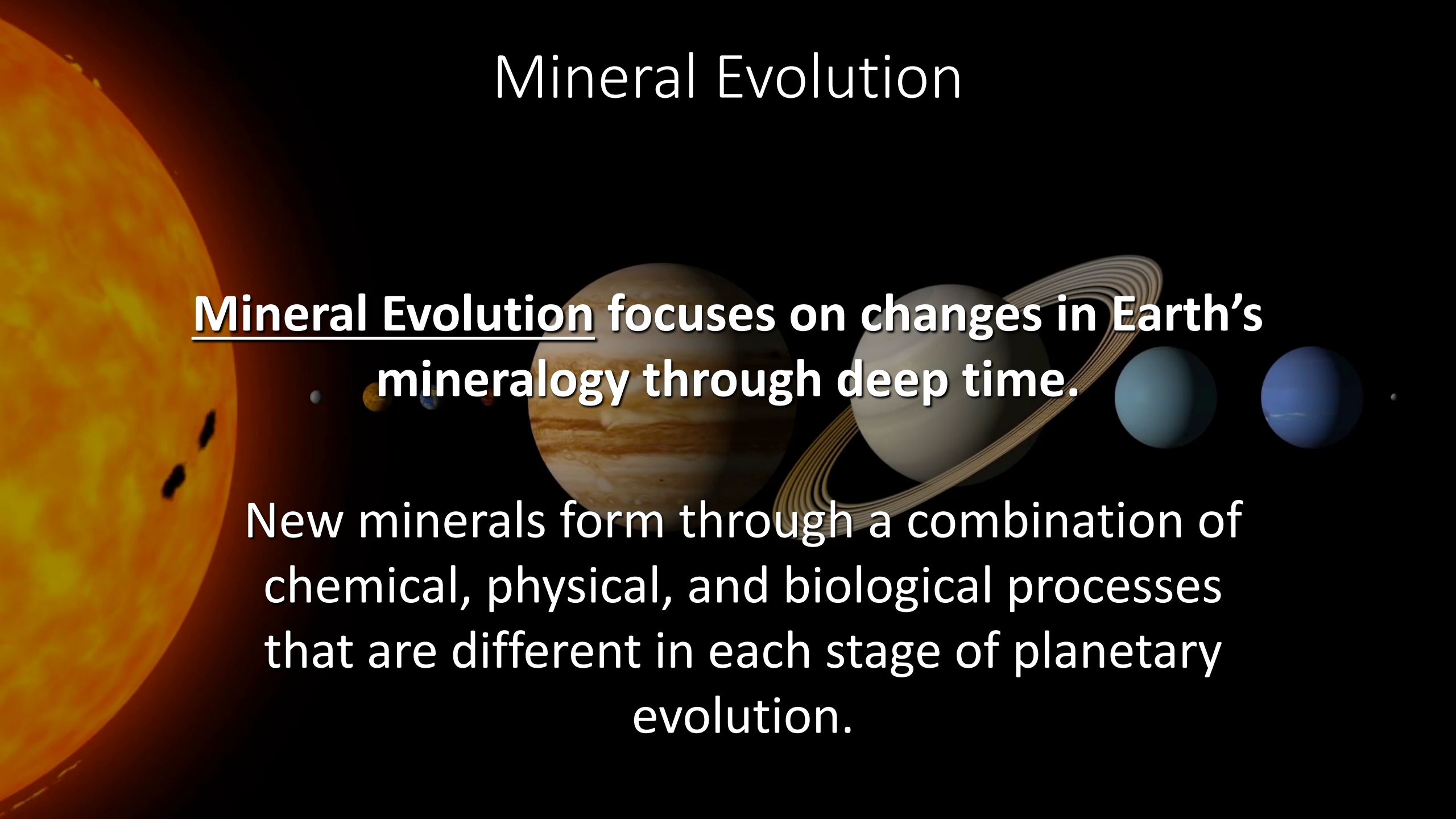
Mineral Evolution

Mineral Evolution



Mineral Evolution focuses on changes in Earth's mineralogy through deep time.

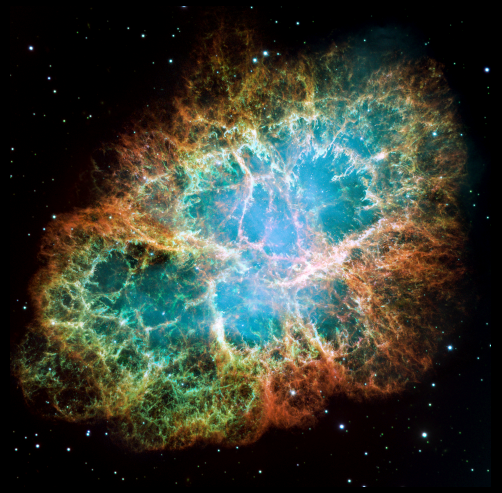
Mineral Evolution



<u>Mineral Evolution</u> focuses on changes in Earth's mineralogy through deep time.

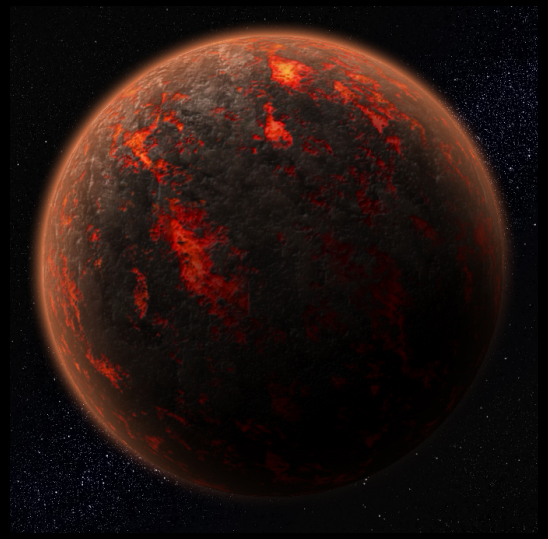
New minerals form through a combination of chemical, physical, and biological processes that are different in each stage of planetary evolution.

Mineral Evolution



Supernova
~12 minerals

Solar Nebula
~60 minerals



Basalt Formation
~500 minerals

Granite Formation
~1000 minerals

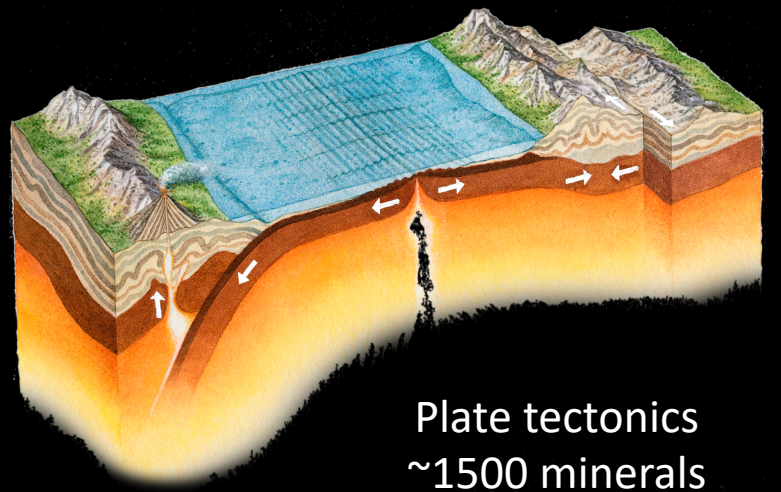
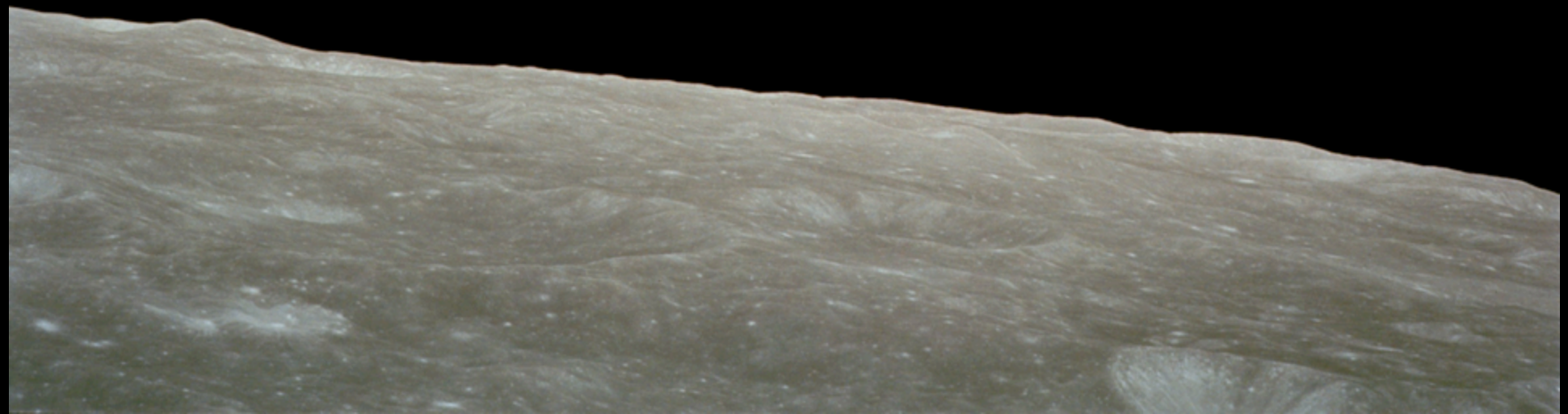


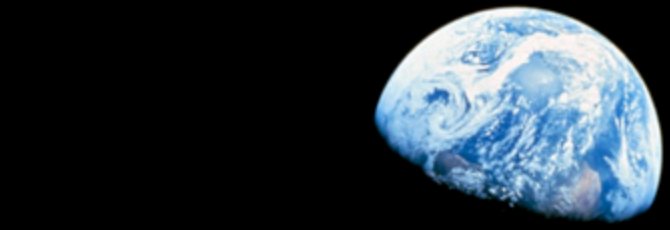
Plate tectonics
~1500 minerals

Mineral Evolution

What caused the explosion of mineral diversity after 2.5 Ga?



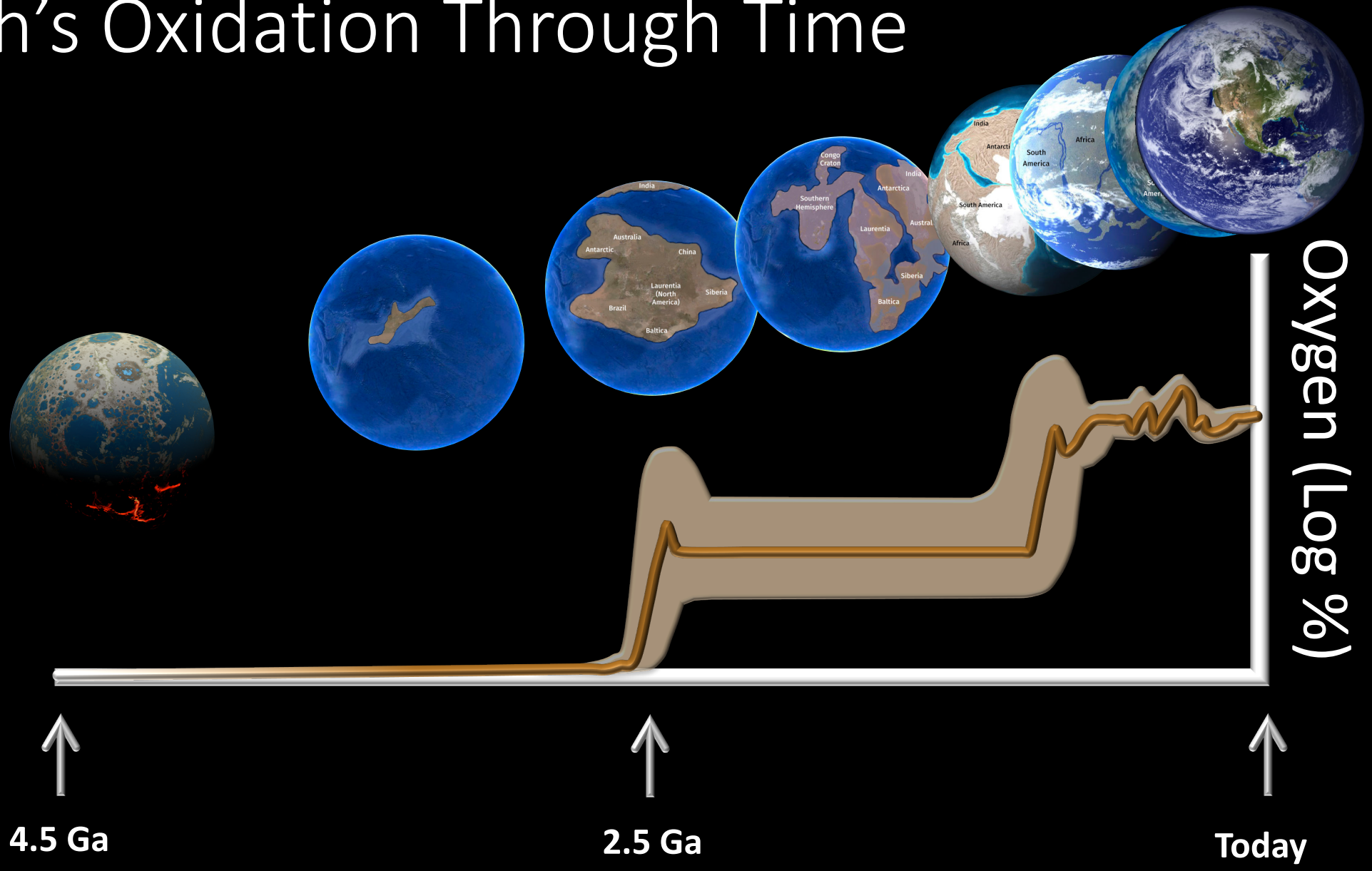
Mineral Evolution



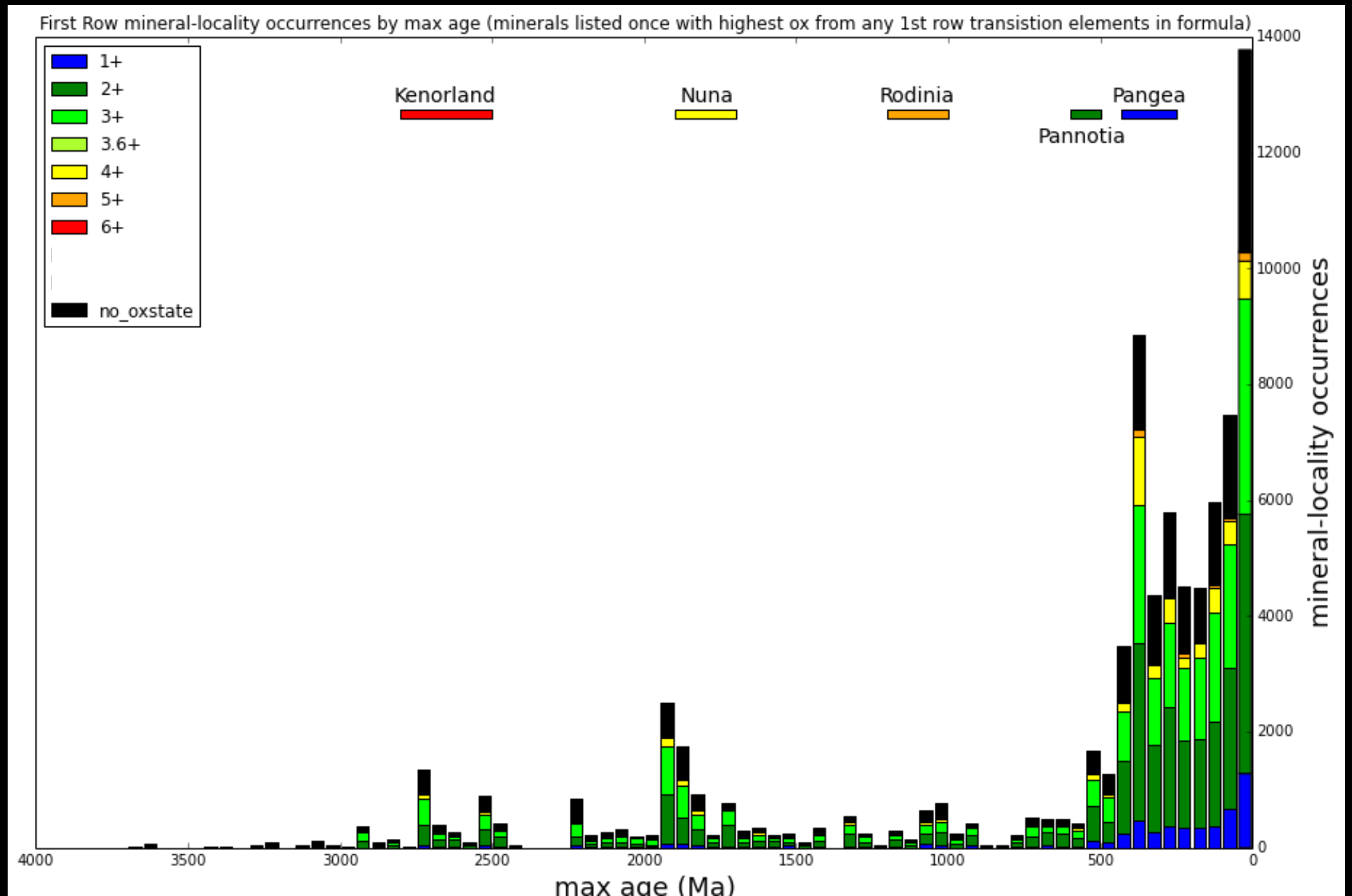
What caused the explosion of mineral diversity after 2.5 Ga?

LIFE

Earth's Oxidation Through Time



Age Distribution of Transition Element Minerals



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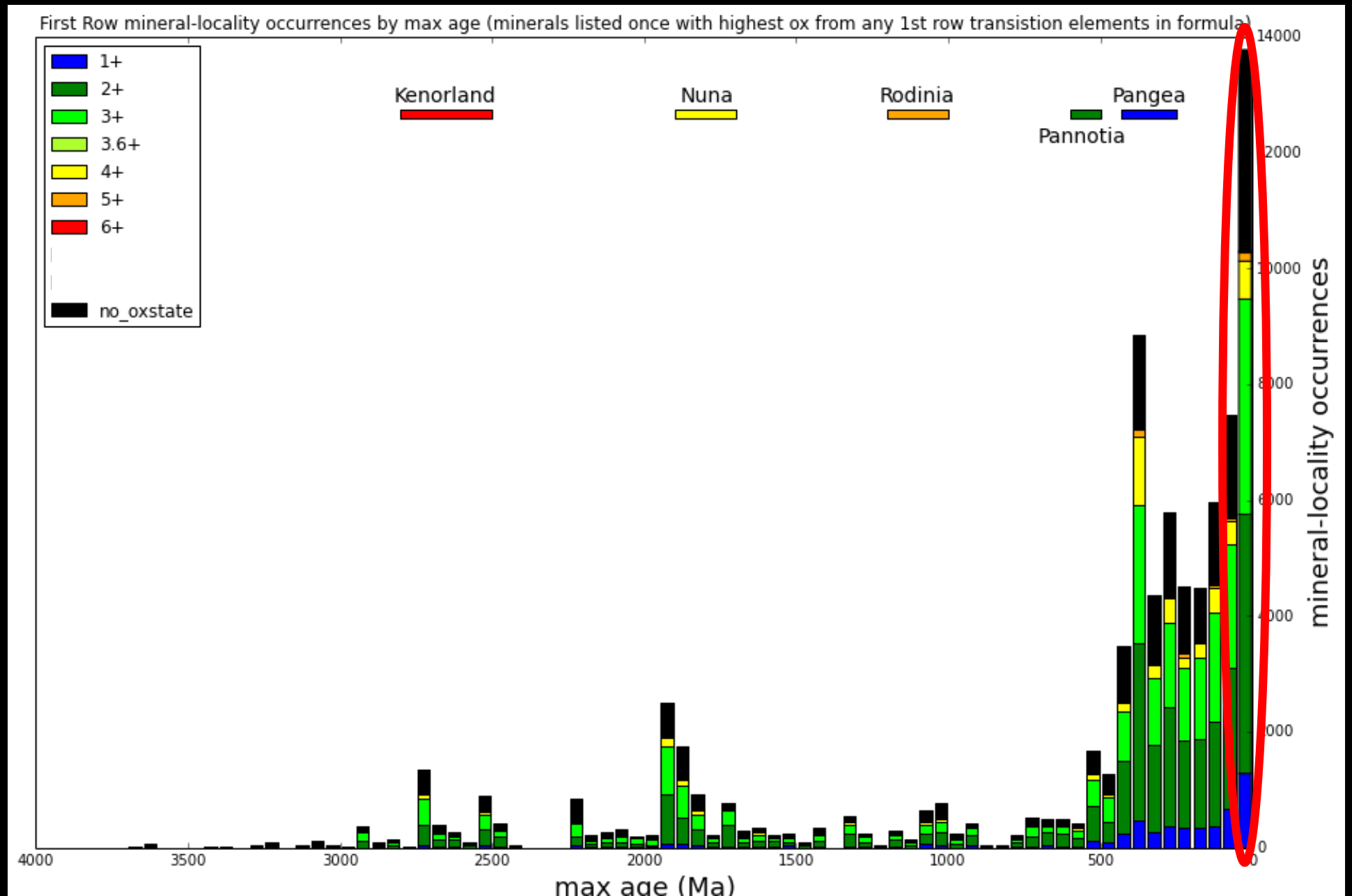

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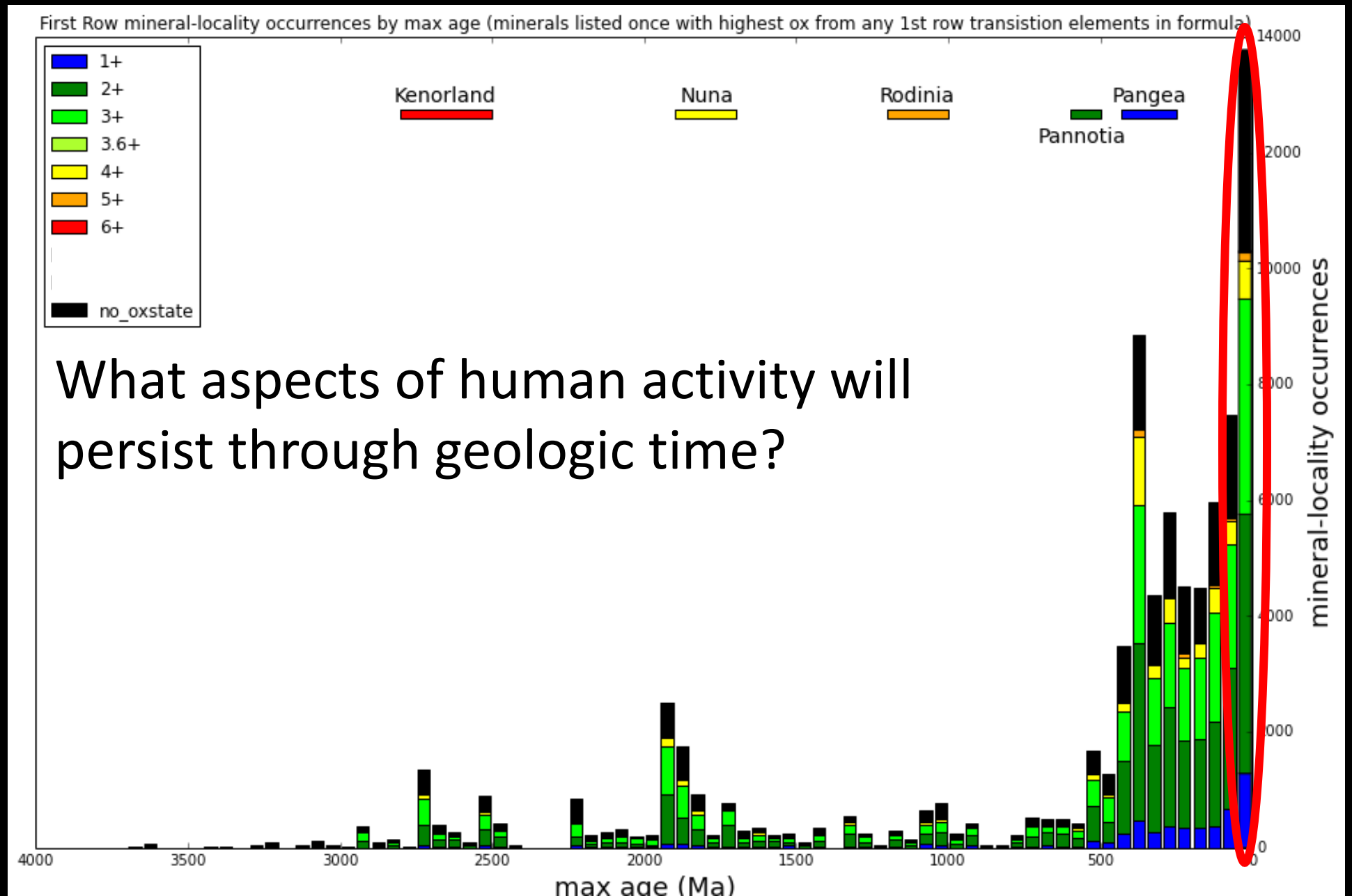

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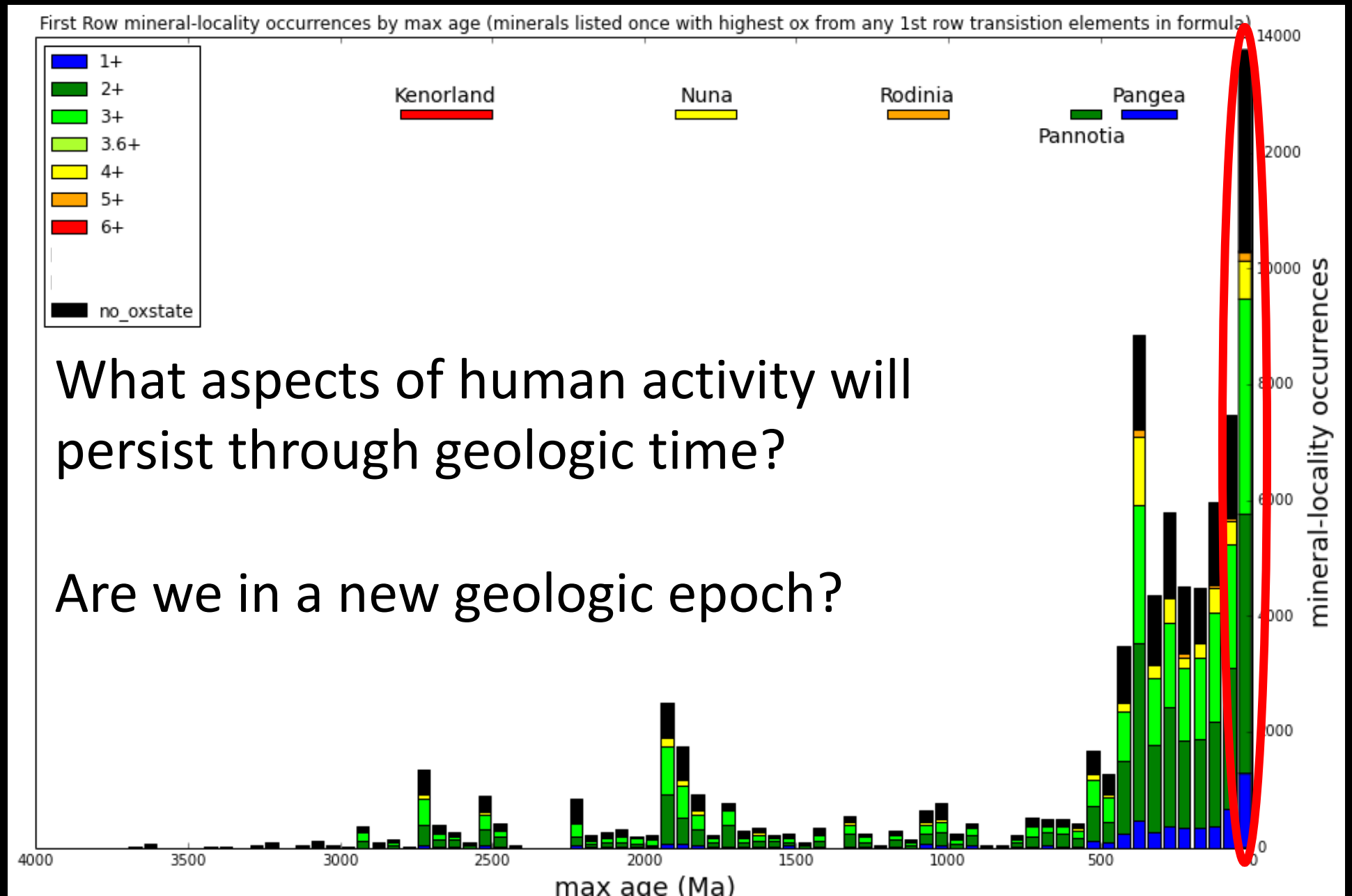


Mineral Evolution: The Anthropocene

Three mineralogical consequences of human activities:

Mineral Evolution: The Anthropocene

Three mineralogical consequences of human activities:

1. New minerals

Mineral Evolution: The Anthropocene

Three mineralogical consequences of human activities:

1. New minerals

2. New mineral-like synthetics

Mineral Evolution: The Anthropocene

Three mineralogical consequences of human activities:

1. New minerals

2. New mineral-like synthetics

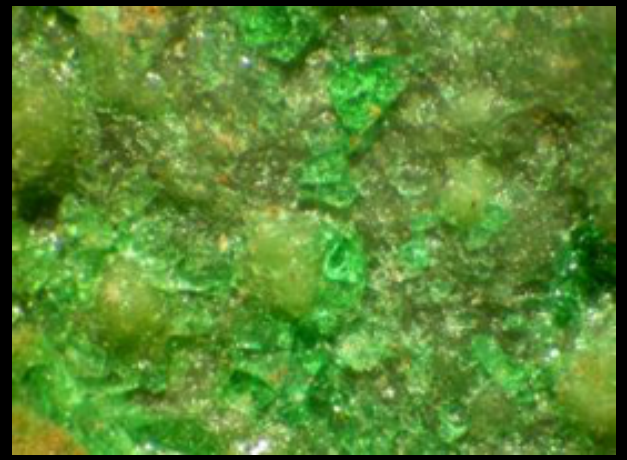
3. Changes in Earth's mineral distribution

Mineral Evolution: The Anthropocene

1. New minerals
- Ore dump minerals

Scheutteite—$Hg_3O_2(SO_4)$

Wheatleyite—$Na_2Cu(C_2O_4)_2 \cdot 2H_2O$



Widgiemoothalite—$Ni_5(CO_3)_4(OH)_2 \cdot 4\text{-}5H_2O$

Mineral Evolution: The Anthropocene

1. New minerals

- Ore dump minerals
- Mine tunnel mineralization

Vysokýite—$U^{4+}[AsO_2(OH)_2]_4 \cdot 4H_2O$

Calciodelroite—$Ca(VO_3)_2 \cdot 4H_2O$

Pseudojohannite—$Cu_3(UO_2)_4O_4(SO_4)_2(OH)_2 \cdot 12H_2O$

Mineral Evolution: The Anthropocene

1. New minerals

- Ore dump minerals
- Mine tunnel mineralization
- Slag and smelter minerals

Cetineite—$NaK_5Sb_{14}S_6O_{18}\cdot 6H_2O$

Fiedlerite—$Pb_3Cl_4F(OH).H_2O$

Thorikosite—$Pb_3O_3Sb^{3+}(OH)Cl_2$

Mineral Evolution: The Anthropocene

1. New minerals

- Ore dump minerals
- Mine tunnel mineralization
- Slag and smelter minerals
- Mine fire minerals

Cuprospinel—$Cu^{2+}Fe^{3+}{}_2O_4$

Lausenite—$Fe^{3+}{}_2(SO_4)_3.5H_2O$

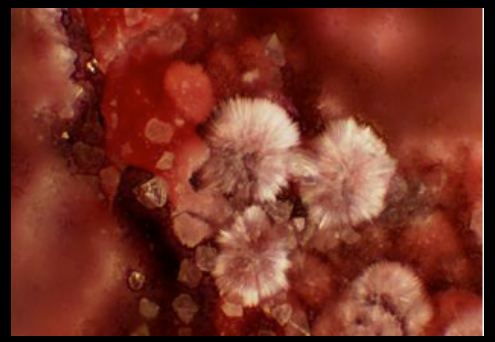
Hoelite—$C_{14}H_8O_2$

Mineral Evolution: The Anthropocene

1. New minerals

- Ore dump minerals
- Mine tunnel mineralization
- Slag and smelter minerals
- Mine fire minerals
- Mine water precipitate minerals

Postitite
$MgAl_2(V_{10}O_{28})(OH)_2 \cdot 27H_2O$

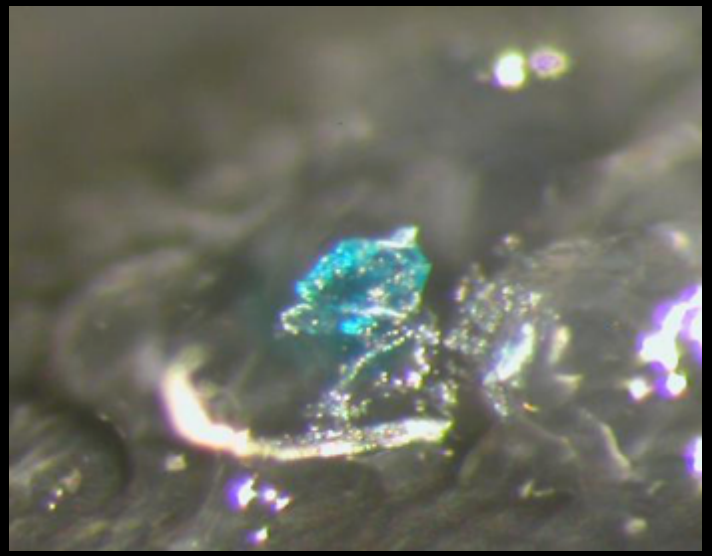


Ferrarisite
$Ca_5(AsO_3OH)_2(AsO_4)_2 \cdot 9H_2O$

Mineral Evolution: The Anthropocene

1. New minerals

- Ore dump minerals
- Mine tunnel mineralization
- Slag and smelter minerals
- Mine fire minerals
- Mine water precipitate minerals
- Mine timber minerals



Hoganite—$Cu(CH_3COO)_2.H_2O$

Mineral Evolution: The Anthropocene

1. New minerals

- Ore dump minerals
- Mine tunnel mineralization
- Slag and smelter minerals
- Mine fire minerals
- Mine water precipitate minerals
- Mine timber minerals
- Geothermal piping minerals

Nasinite—$Na_2B_5O_8(OH).2H_2O$

Mineral Evolution: The Anthropocene

1. New minerals

- Ore dump minerals
- Mine tunnel mineralization
- Slag and smelter minerals
- Mine fire minerals
- Mine water precipitate minerals
- Mine timber minerals
- Geothermal piping minerals
- Weathering of waste

Electronics

Cars

Mineral Evolution: The Anthropocene

2. New mineral-like synthetics

Mineral Evolution: The Anthropocene

2. New mineral-like synthetics

- Two broad categories:

Mineral Evolution: The Anthropocene

2. New mineral-like synthetics

- Two broad categories:

- Construction, agricultural, and other bulk products with mineral-like composition and structure

Mineral Evolution: The Anthropocene

2. New mineral-like synthetics

- Two broad categories:

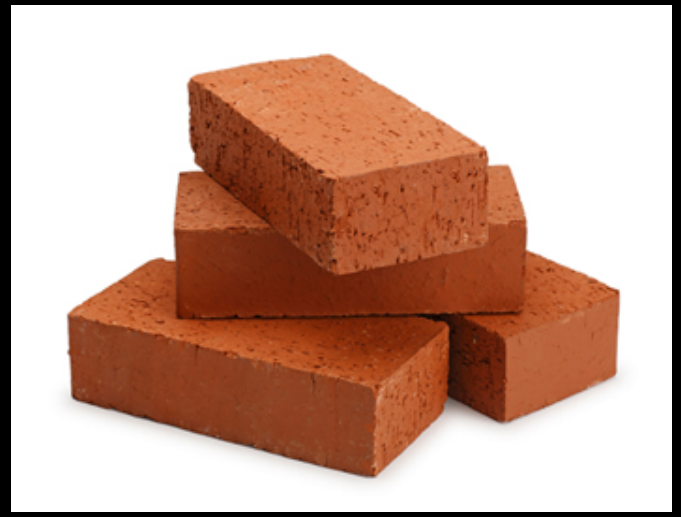
- Construction, agricultural, and other bulk products made up of minerals

- Synthetic crystalline materials for specialized applications

Mineral Evolution: The Anthropocene

2. New mineral-like synthetics

- Bricks, cement, lime, plaster



Mineral Evolution: The Anthropocene

2. New mineral-like synthetics

- Bricks, cement, lime, plaster
- Earthenware and porcelain

Mineral Evolution: The Anthropocene

2. New mineral-like synthetics

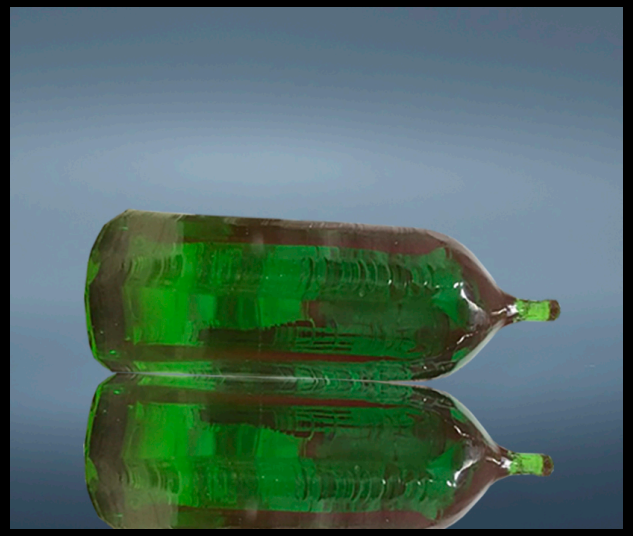
- Bricks, cement, lime, plaster
- Earthenware and porcelain
- Abrasives: alumina, diamond, carbides

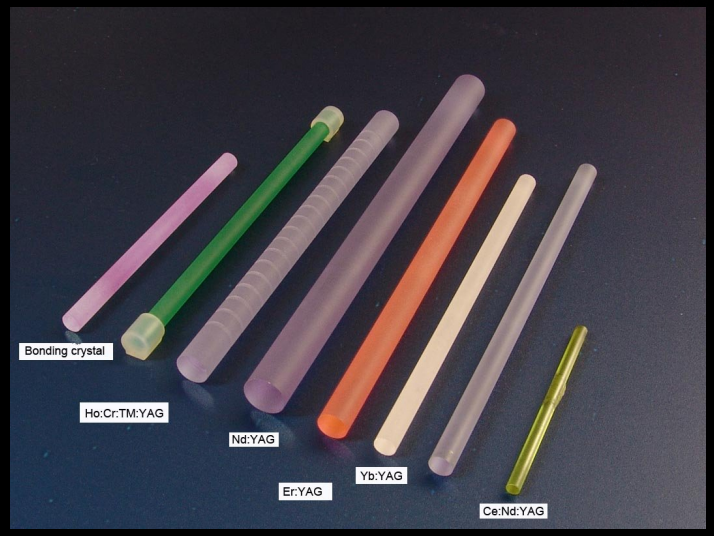
Diamond grinding wheel

Mineral Evolution: The Anthropocene

2. New mineral-like synthetics

- Bricks, cement, lime, plaster
- Earthenware and porcelain
- Abrasives: alumina, diamond, c
- Laser crystals: ruby, YAG

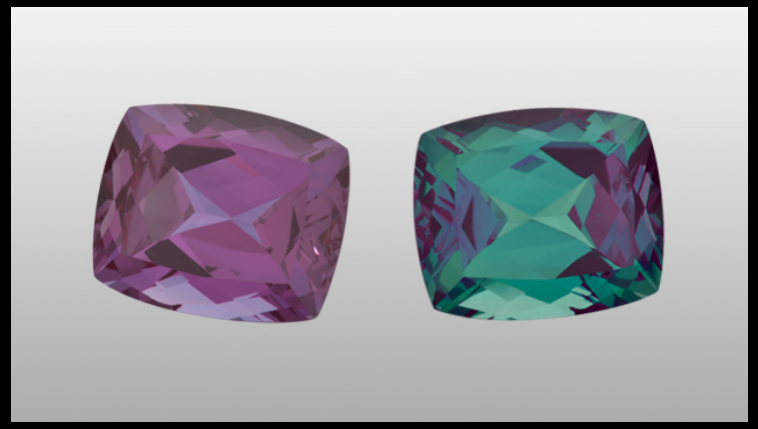


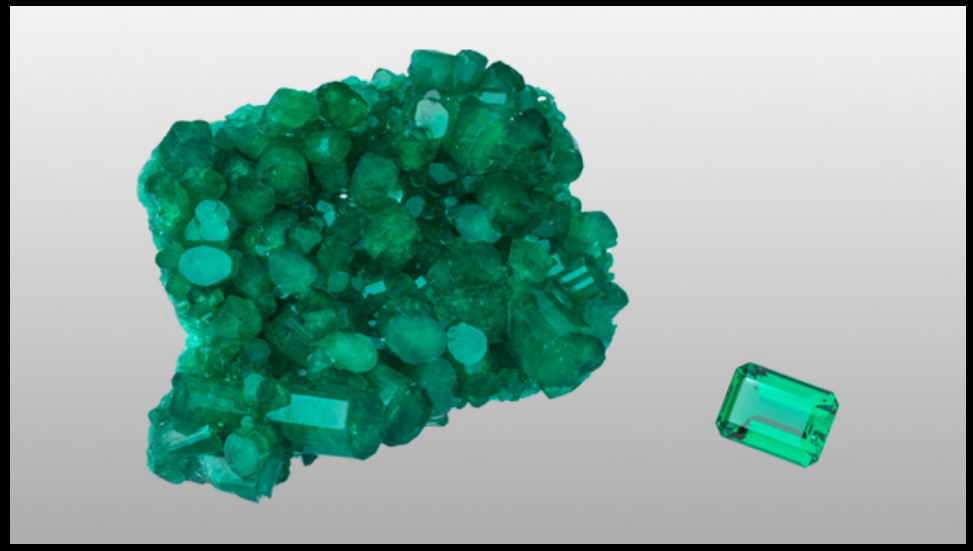


Mineral Evolution: The Anthropocene

2. New mineral-like synthetics

- Bricks, cement, lime, plaster
- Earthenware and porcelain
- Abrasives: alumina, diamond, carb
- Laser crystals: ruby, YAG
- Synthetic gemstones

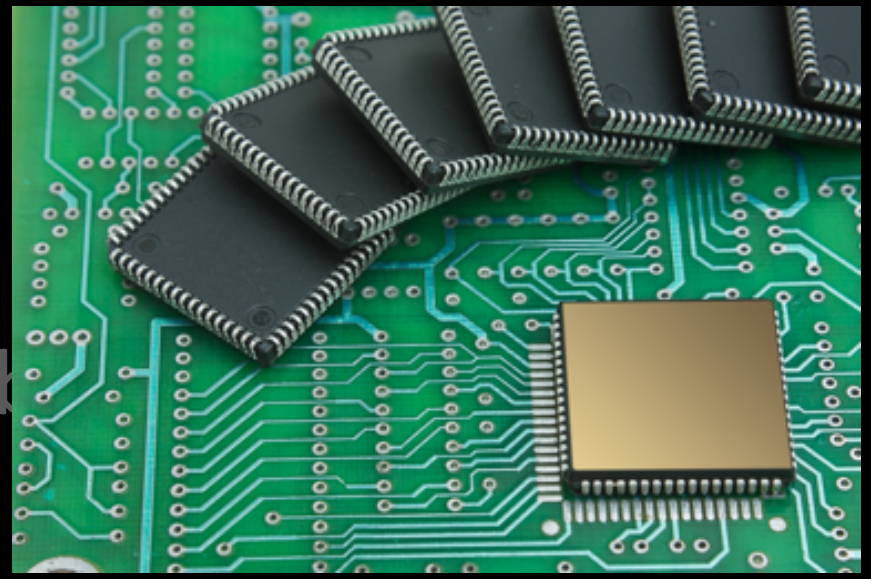


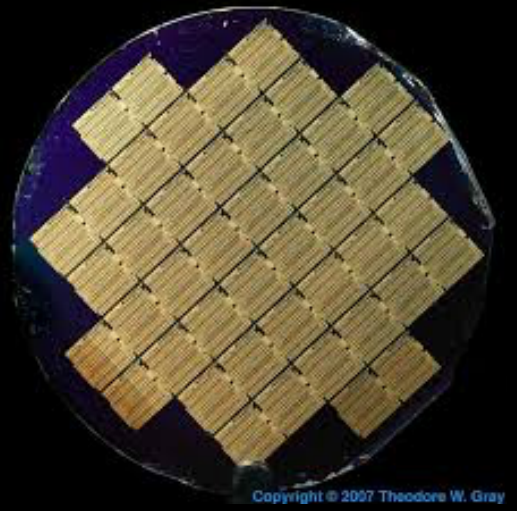


Mineral Evolution: The Anthropocene

2. New mineral-like synthetics

- Bricks, cement, lime, plaster
- Earthenware and porcelain
- Abrasives: alumina, diamond, carb
- Laser crystals: ruby, YAG
- Synthetic gemstones
- Semiconductors: silicon, gallium arsenide

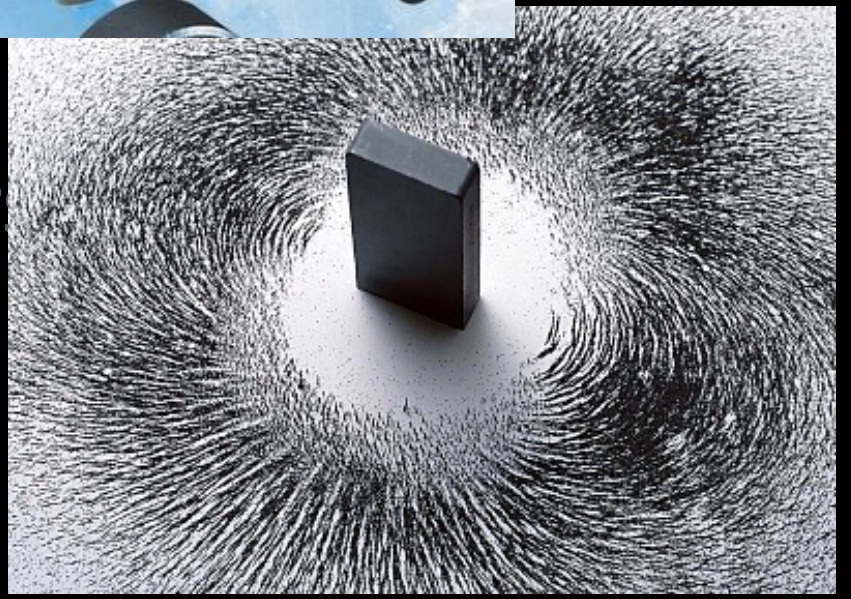




Mineral Evolution: The Anthropocene

2. New mineral-like synthetic

- Bricks, cement, lime, plast
- Earthenware and porcelai
- Abrasives: alumina, diamo
- Laser crystals: ruby, YAG
- Synthetic gemstones
- Semiconductors: silicon, gallium ar
- Magnets: ferrite, REE, cobalt alloy



Mineral Evolution: The Anthropocene

2. New mineral-like synthetics

- Bricks, cement, lime, plaster
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- Metal alloys

Mineral Evolution: The Anthropocene

3. Changes in Earth’s distribution of minerals

Mineral Evolution: The Anthropocene

3. Changes in Earth's distribution of minerals

- Mining and quarrying

Mineral Evolution: The Anthropocene

3. Changes in Earth's distribution of minerals

- Mining and quarrying
- Underground cables, sewers, and conduits

Mineral Evolution: The Anthropocene

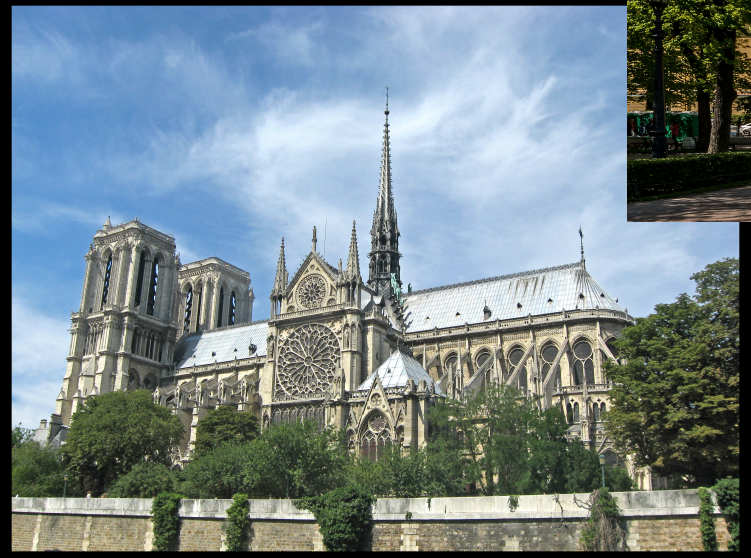
3. Changes in Earth's distribution of minerals

- Mining and quarrying
- Underground cables, sewers, and con
- Stone monuments

Mineral Evolution: The Anthropocene

3. Changes in Earth's distribution of minerals

- Mining and quarrying
- Underground cables, sewers, and
- Stone monuments
- Stone buildings



Mineral Evolution: The Anthropocene

3. Changes in Earth's distribution of minerals

- Mining and quarrying
- Underground cables, sewers, and conc
- Stone monuments
- Stone buildings
- Carved and faceted minerals

Mineral Evolution: The Anthropocene

3. Changes in Earth's distribution of minerals

- Mining and quarrying
- Underground cables, sew
- Stone monuments
- Stone buildings
- Carved and faceted mine
- Breakwaters, revetments, piers

Mineral Evolution: The Anthropocene

3. Changes in Earth's distribution of minerals

- Mining and quarrying
- Underground cables, sewers, a
- Stone monuments
- Stone buildings
- Carved and faceted mine
- Breakwaters, revetments
- Mineral collections

Mineral Evolution: The Anthropocene

Humans are having a dramatic, global effect on the mineralogy and sedimentology of our planet.

We are creating a robust, distinct stratigraphic horizon
&
A new stage of mineral evolution

Mineral Evolution: The Anthropocene

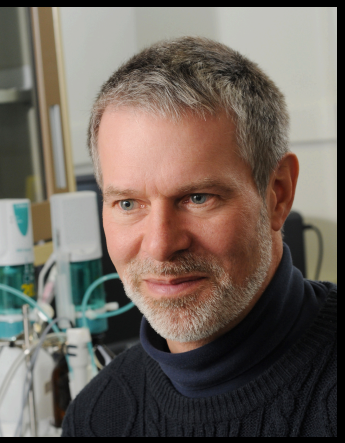
Therefore, this new stratigraphic horizon corresponds to a new geologic time interval:

Mineral Evolution: The Anthropocene

Therefore, this new stratigraphic horizon corresponds to a new geologic time interval:

The Anthropocene Epoch

Data-driven projects and discoveries

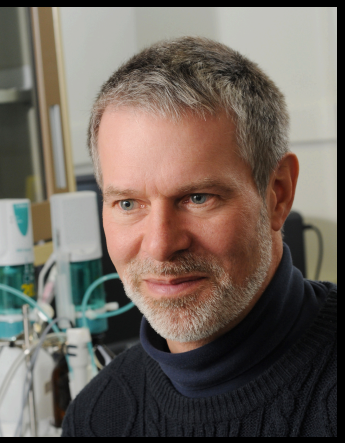


Bob Hazen

Data-driven projects and discoveries: Mineral Ecology

Grethe Hystad

<u>Mineral Ecology</u> focuses on the diversity and distribution of minerals on Earth's surface.



Bob Hazen

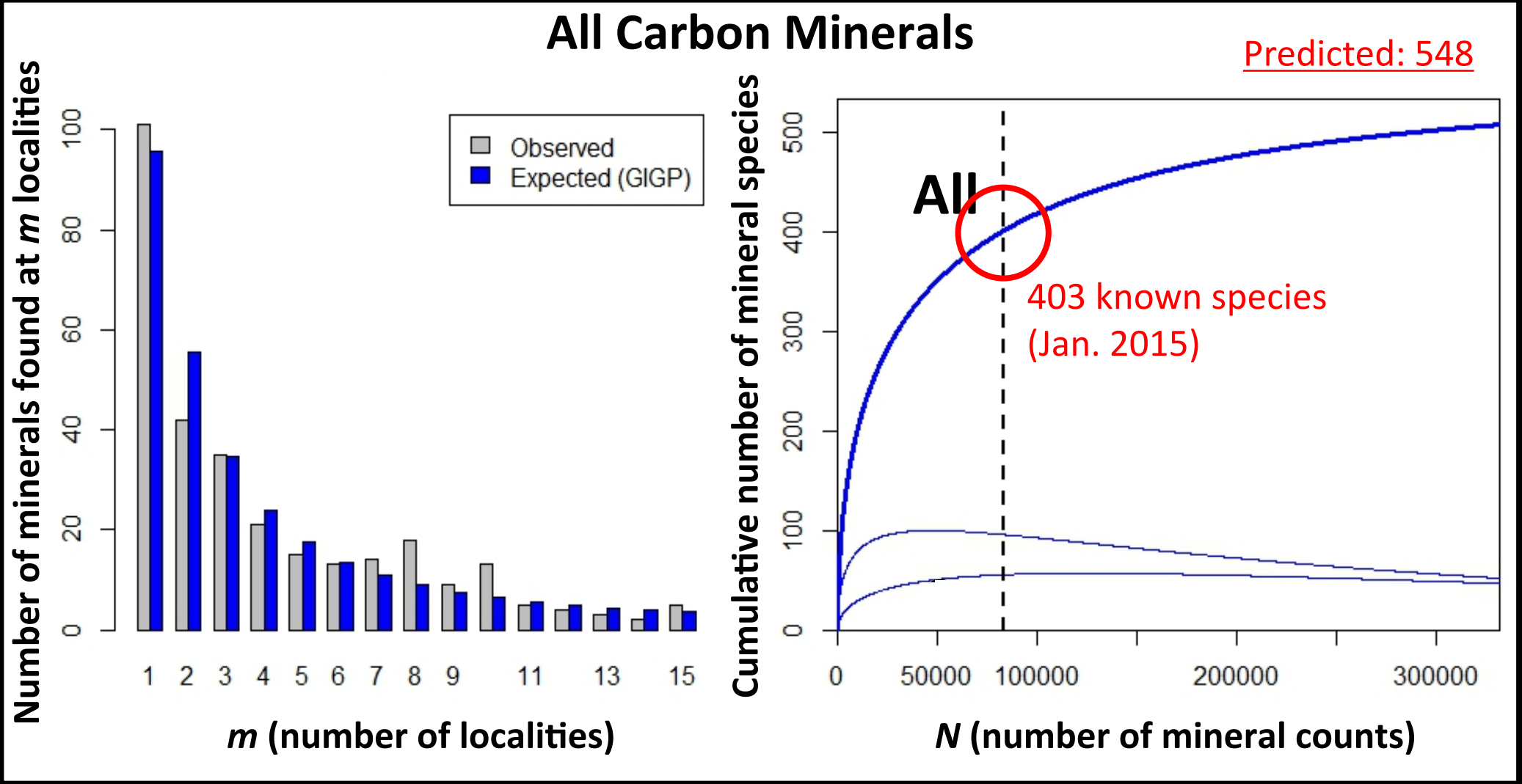
Data-driven projects and discoveries: Mineral Ecology

Grethe Hystad

<u>Mineral Ecology</u> focuses on the diversity and distribution of minerals on Earth's surface.

LNRE = Most minerals are rare, only a few are very common

Hystad et al. 2015



145 ”missing” carbon minerals

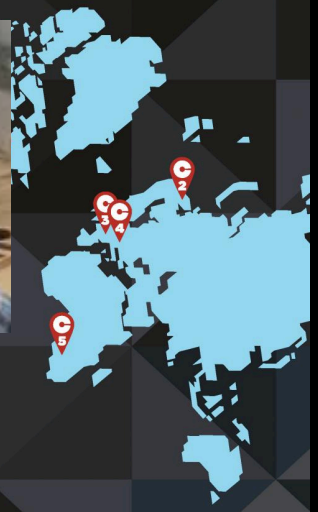
American Mineralogist, Volume 101, pages 889–906, 2016

Carbon mineral ecology: Predicting the undiscovered minerals of carbon

ROBERT M. HAZEN[1,*], DANIEL R. HUMMER[1], GRETHE HYSTAD[2], ROBERT T. DOWNS[3], AND JOSHUA J. GOLDEN[3]

The CARBON MINERAL CHALLENGE

Dan Hummer

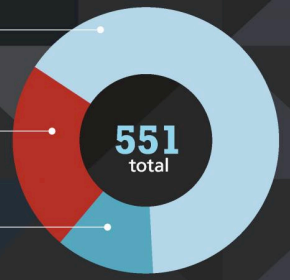


A worldwide hunt for new carbon minerals
mineralchallenge.net

406
already known carbon minerals

145*
predicted undiscovered carbon minerals

75
carbon minerals described since 2000



2019
the year the Deep Carbon Observatory will celebrate its accomplishments, including the minerals discovered during the Carbon Mineral Challenge

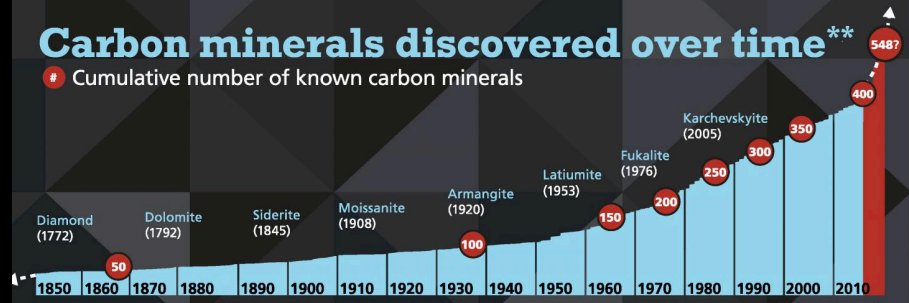
Places known to have the greatest diversity of carbon minerals

- C1 Poudrette Quarry Mont Saint-Hilaire, Québec, Canada
- C2 Kukisvumchorr Mt, Khibiny Massif, Kola Peninsula, Russia
- C3 Clara Mine, Wolfach, Baden-Württemberg, Germany
- C4 Jáchymov, Karlovy Vary Region, Bohemia, Czech Republic
- C5 Tsumeb Mine, Tsumeb, Namibia

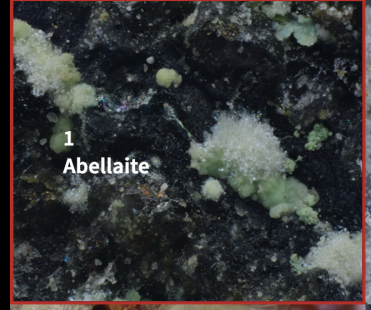
Surveys of localities with the greatest diversity of carbon minerals point to promising locations for the discovery of as yet undescribed minerals

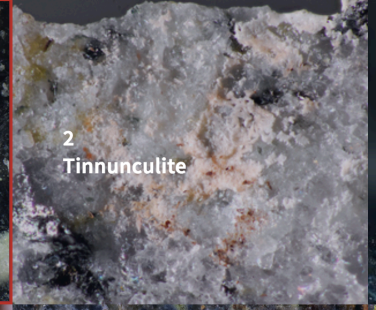
Carbon minerals discovered over time**

Cumulative number of known carbon minerals



* Based on model and statistical analyses, by Hazen, Hummer, Hystad, Downs, and Golden, *American Mineralogist* (in press).
** Year first reported in scientific literature.

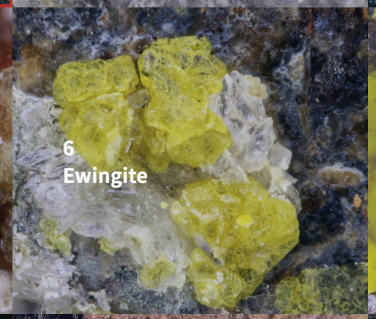

1 Abellaite

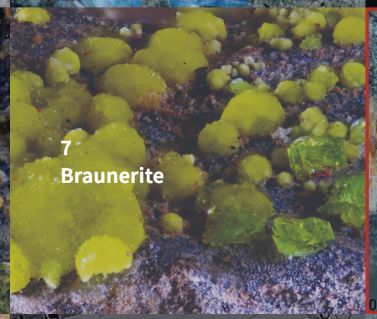

2 Tinnunculite


3 Marklite

4 Middlebackite

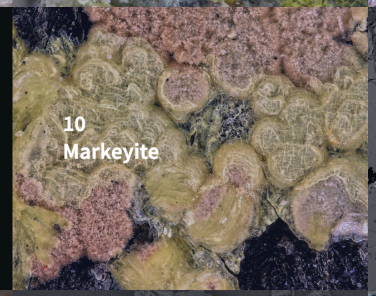

5 Leószilárdite

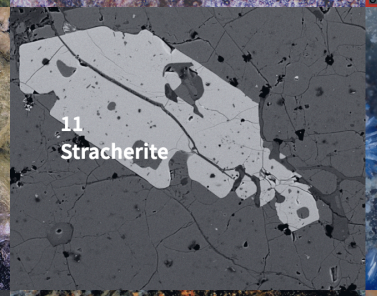

6 Ewingite


7 Braunerite

8 Parisite-(La)

9 Roymillerite


10 Markeyite


11 Stracherite


12 Triazolite


13 Somersetite


14 Marchettiite


15 Ramazzoite


16 Paddlewheelite

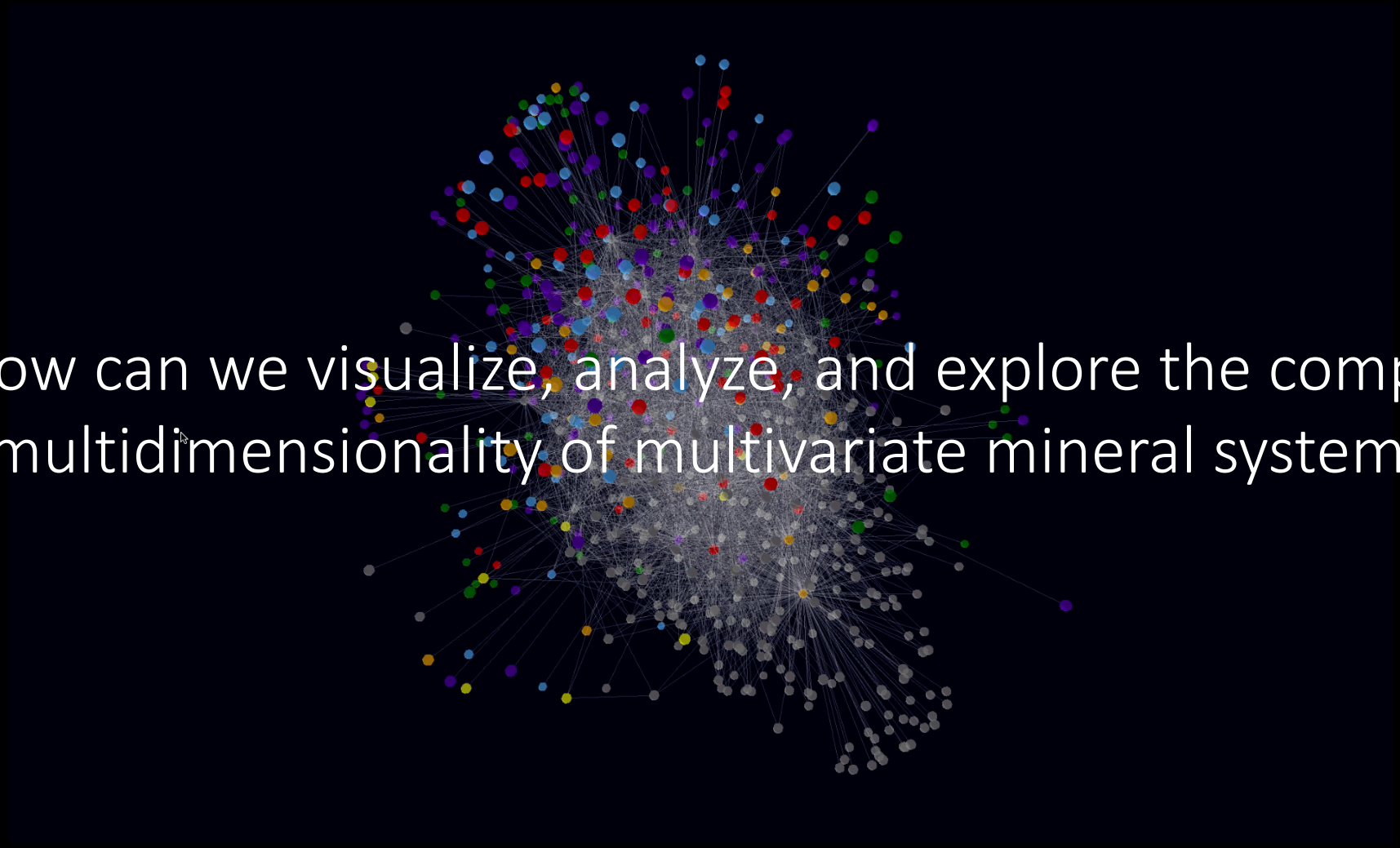
17 Phoxite

18 Fiemmeite

19 Meyrowitzite

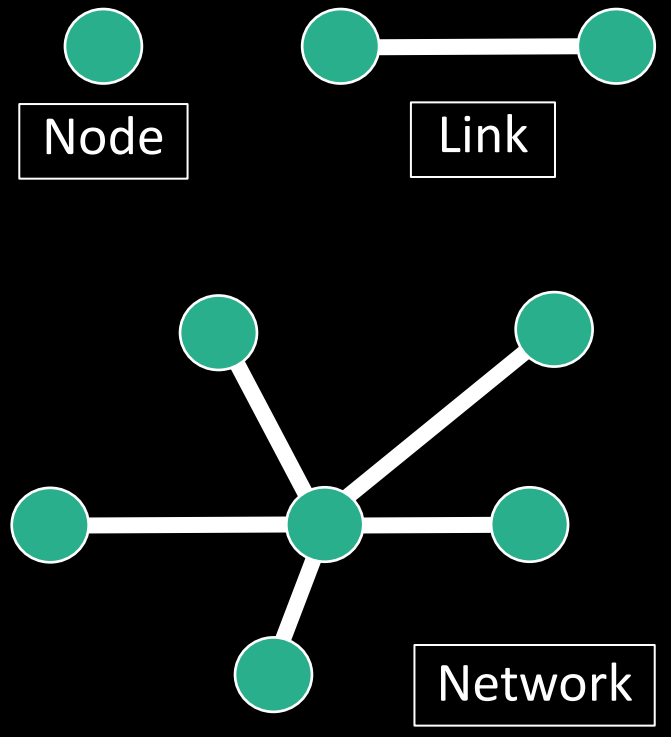
20 Alterite

Data-driven projects and discoveries: Mineral Networks



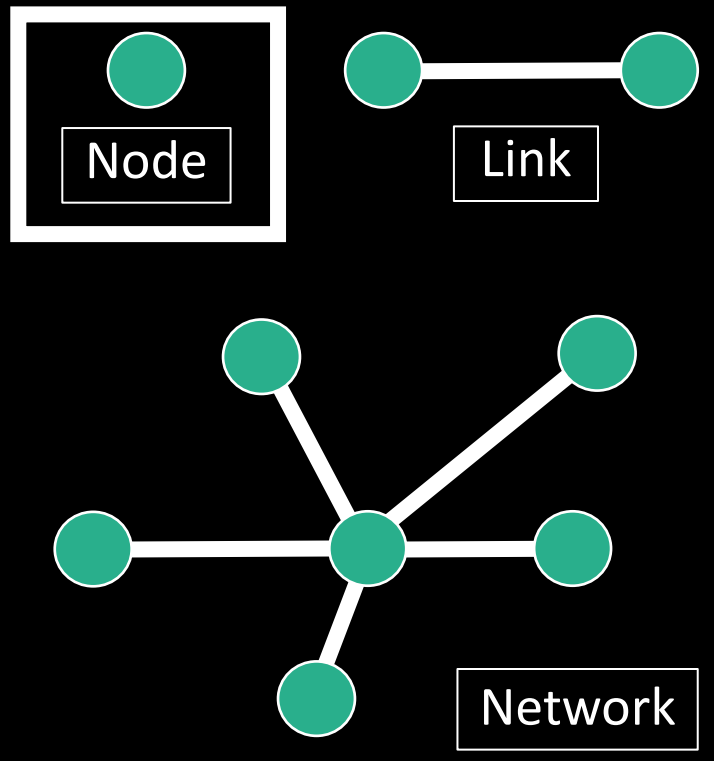
How can we visualize, analyze, and explore the complex multidimensionality of multivariate mineral systems?

Data-driven projects and discoveries: Mineral Networks



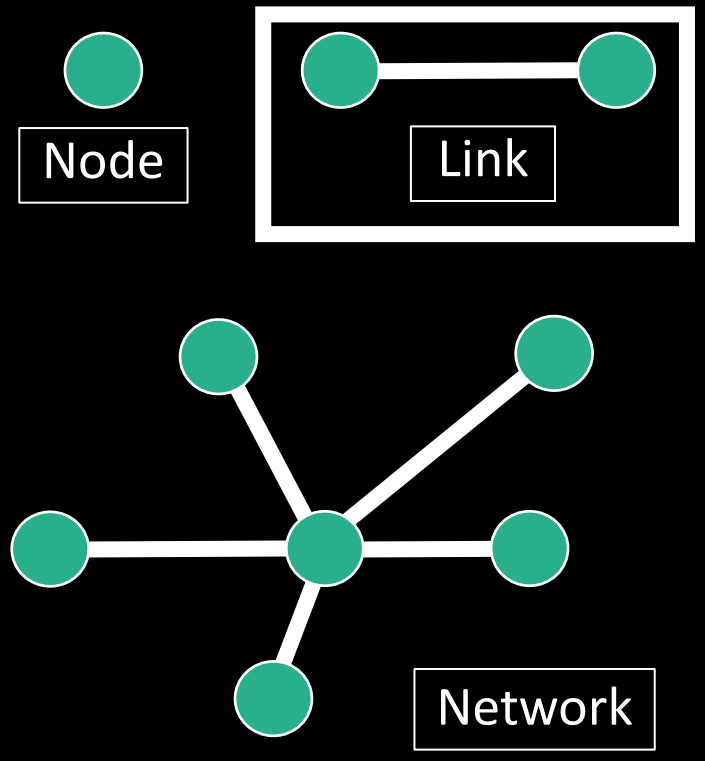
Data-driven projects and discoveries: Mineral Networks

- Node ⟶ Mineral



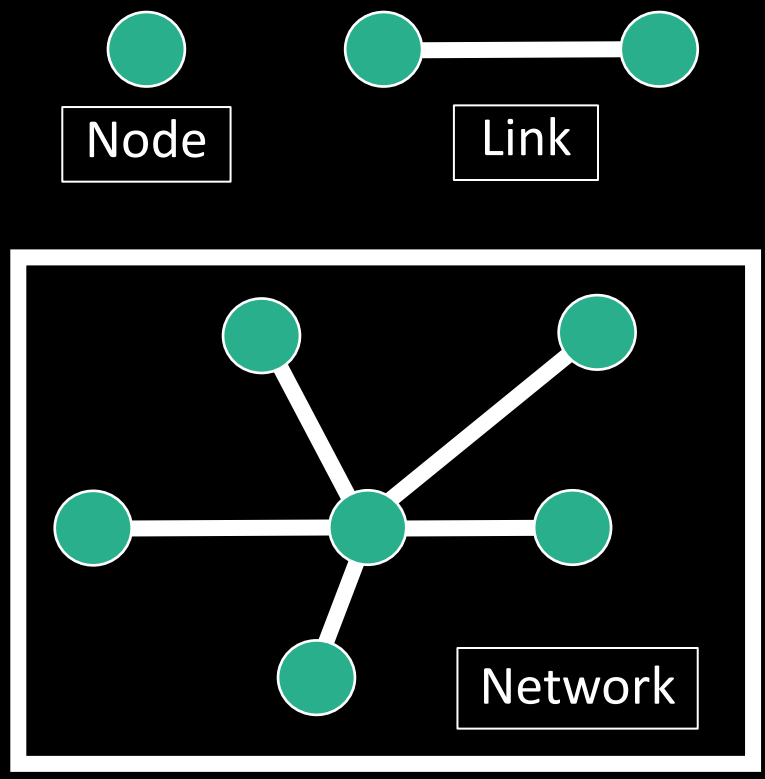
Data-driven projects and discoveries: Mineral Networks

- Node ⟶ Mineral
- Link ⟶ Co-occurrence



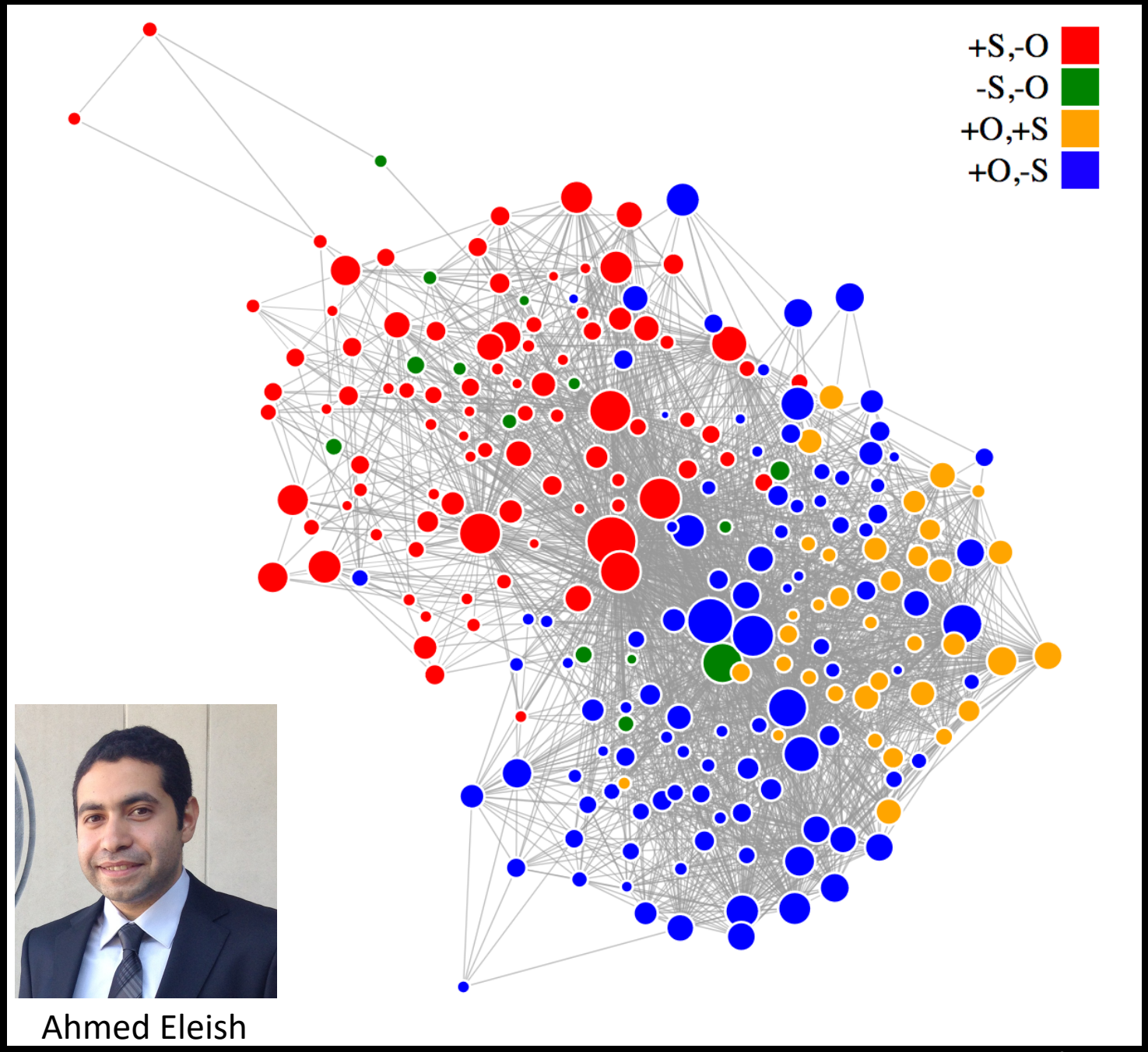
Data-driven projects and discoveries: Mineral Networks

- Node → Mineral
- Link → Co-occurrence
- Network →
  - Element
  - Deposit
  - Rock type
  - Planet



Cu mineral network

- Force-directed layout
- Nodes
  - Color: chemistry
  - Size: no. of localities
- Links:
  - Length: co-occurrence
- High density
- High centralization



Ahmed Eleish

Morrison et al. 2017

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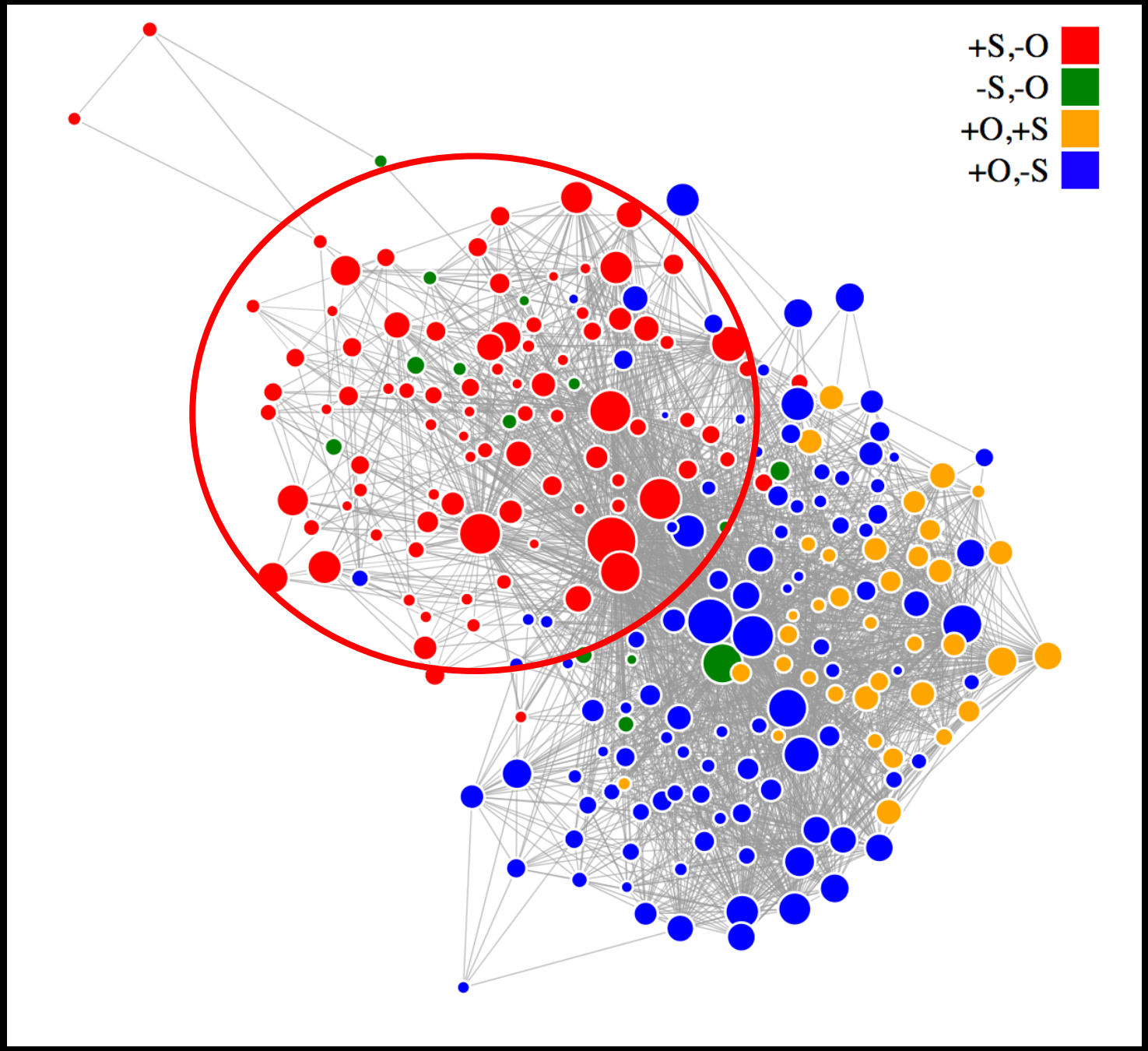

Morrison et al. 2017

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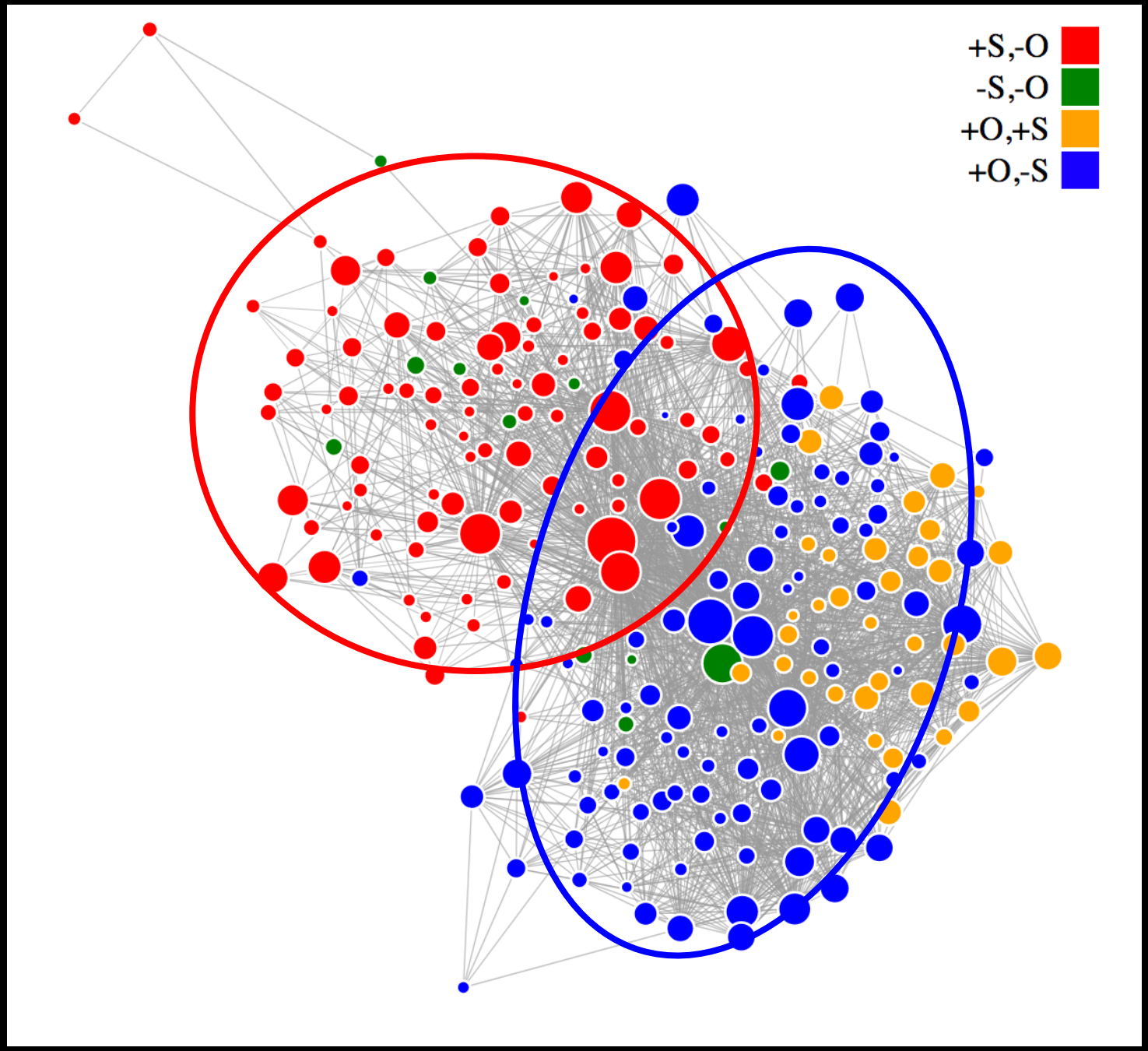

Morrison et al. 2017

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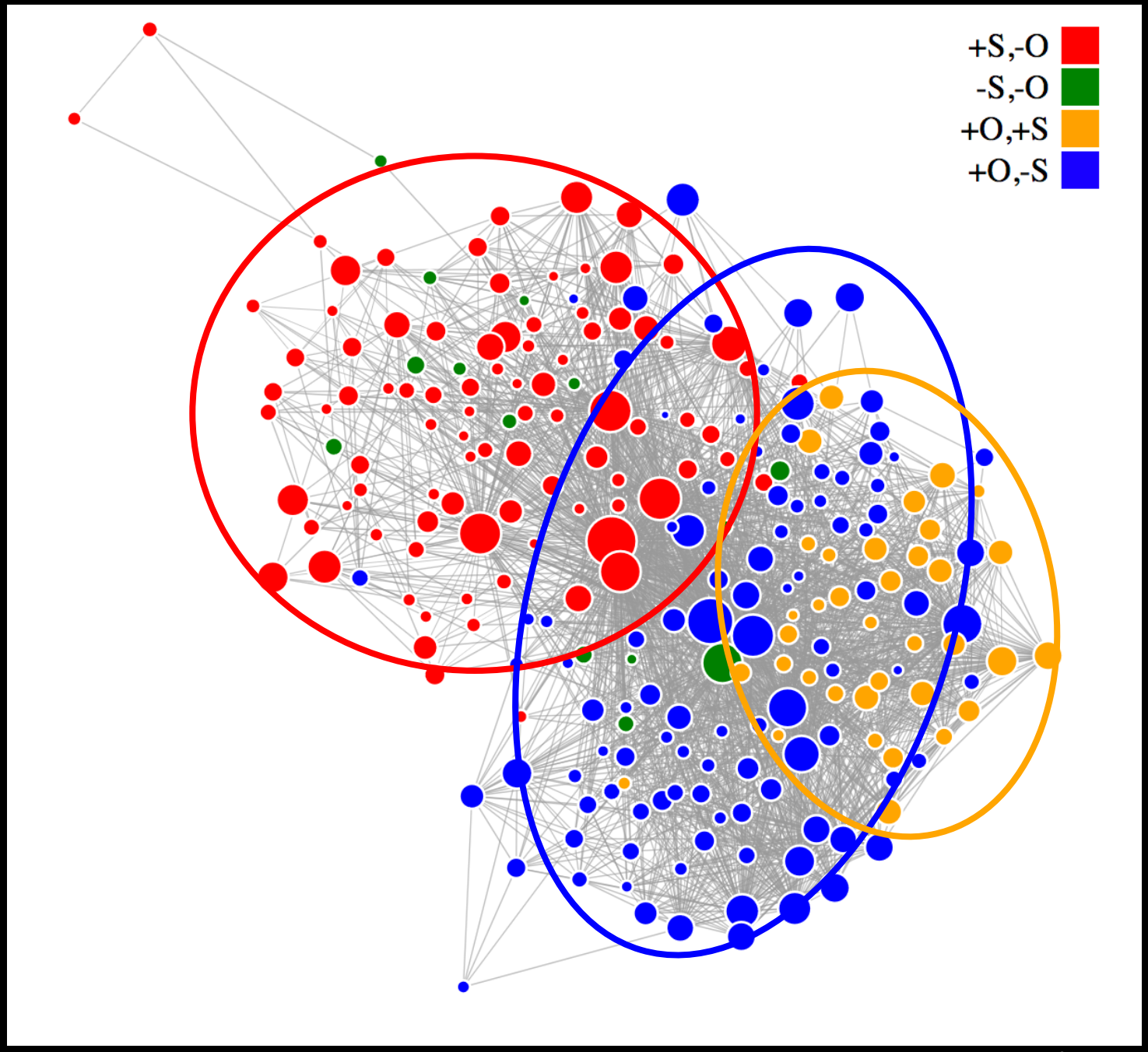

Morrison et al. 2017

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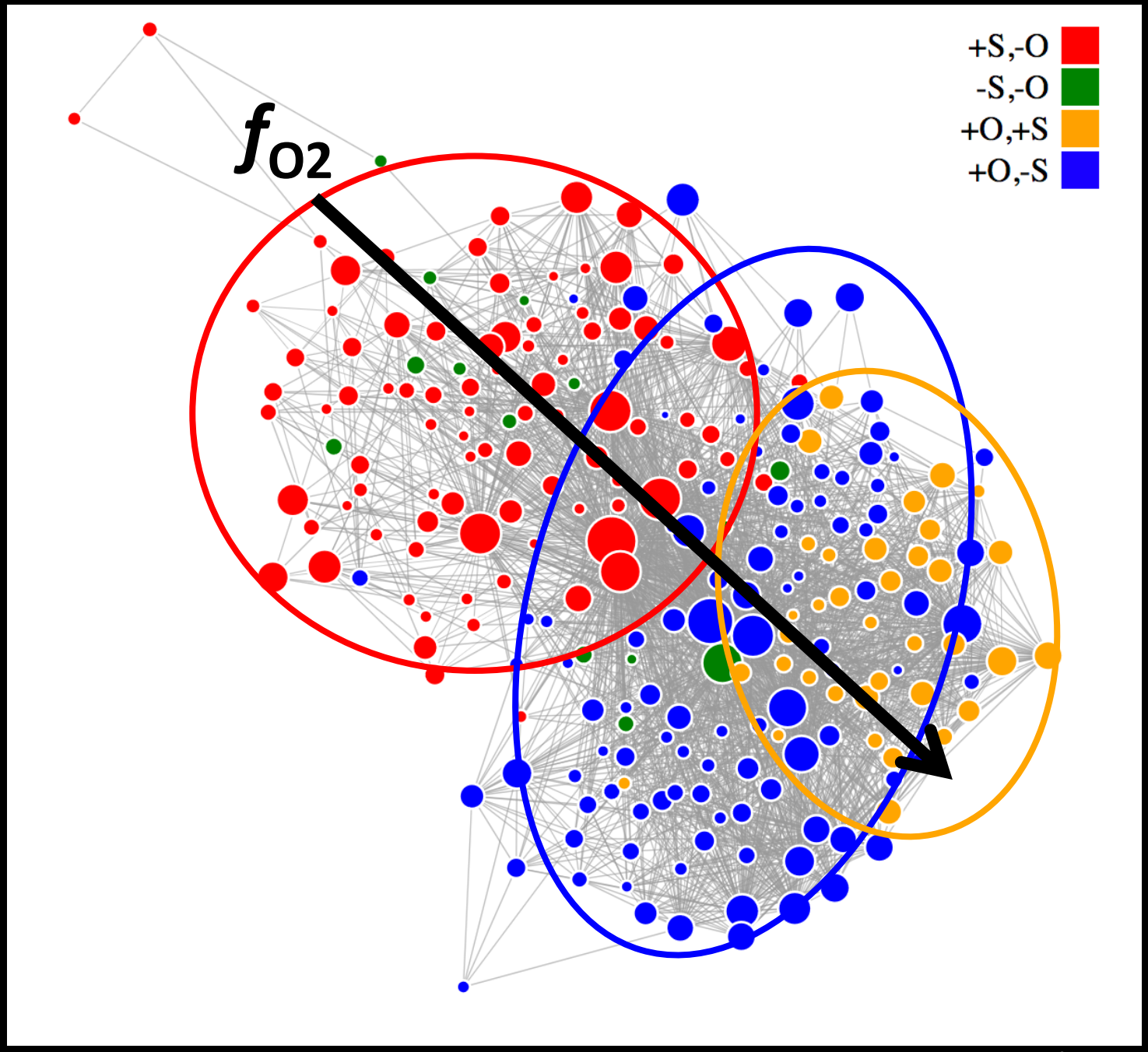

Morrison et al. 2017

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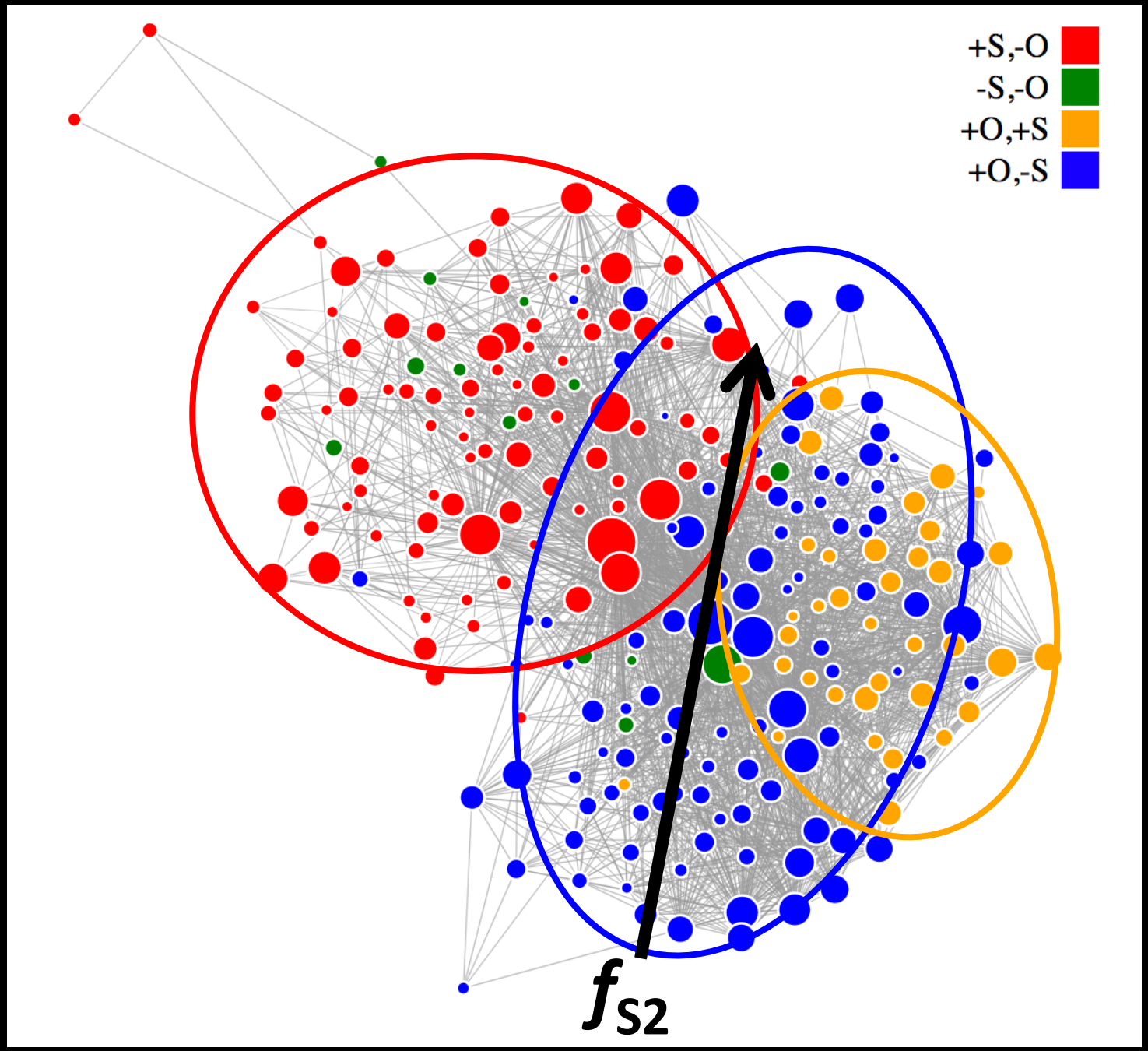
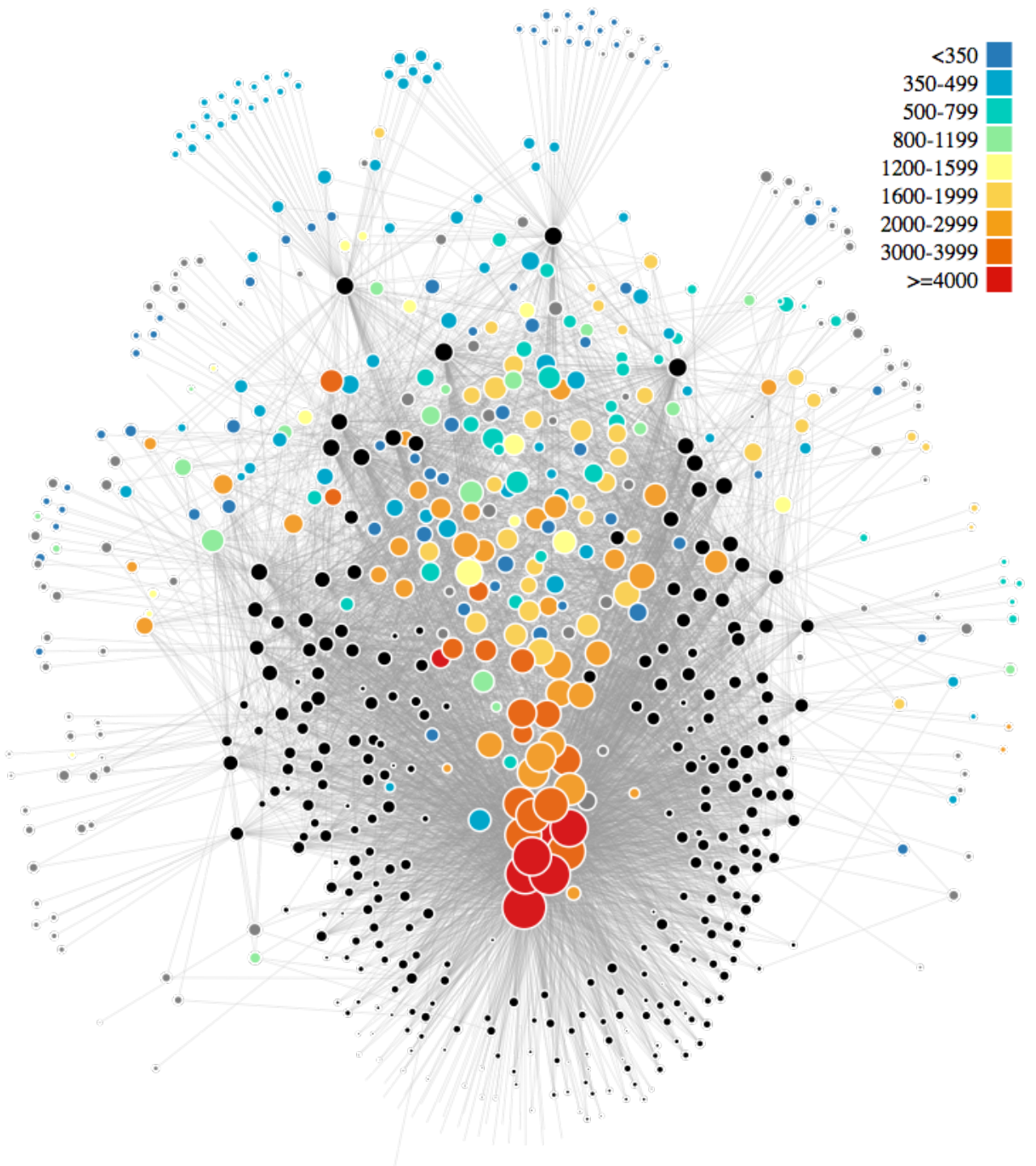


Morrison et al. 2017

Carbon mineral-locality network

- Bipartite, force-directed layout
- Mineral nodes
  - Color & Size: no. of localities
- Locality nodes
  - Size: mineral diversity



Hazen et al. 2019; Morrison et al. 2019

Carbon mineral-locality network

- Bipartite, force-directed layout
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  - Color & Size: no. of localities
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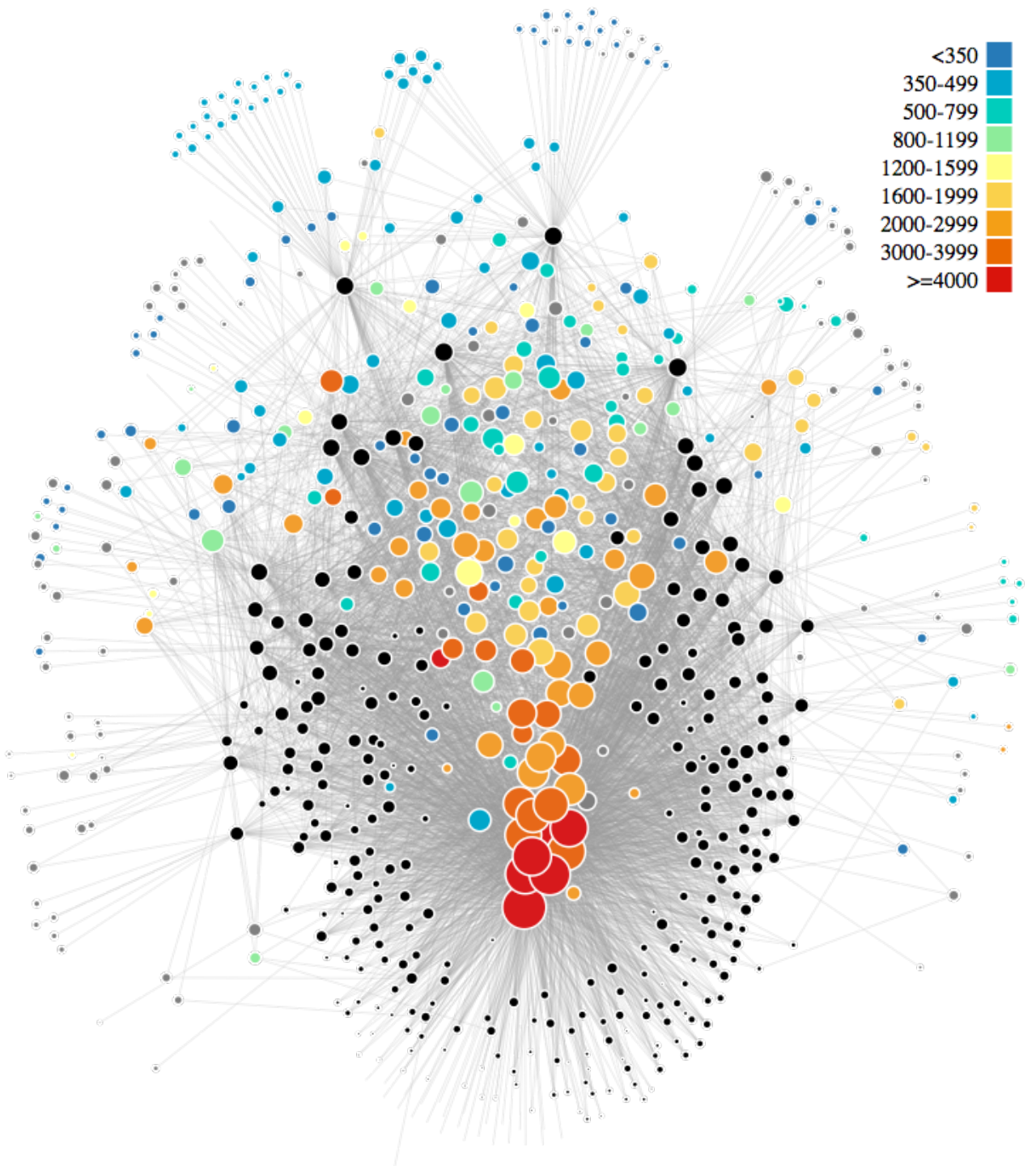
1. Biosignature



Hazen et al. 2019; Morrison et al. 2019

Carbon mineral-locality network

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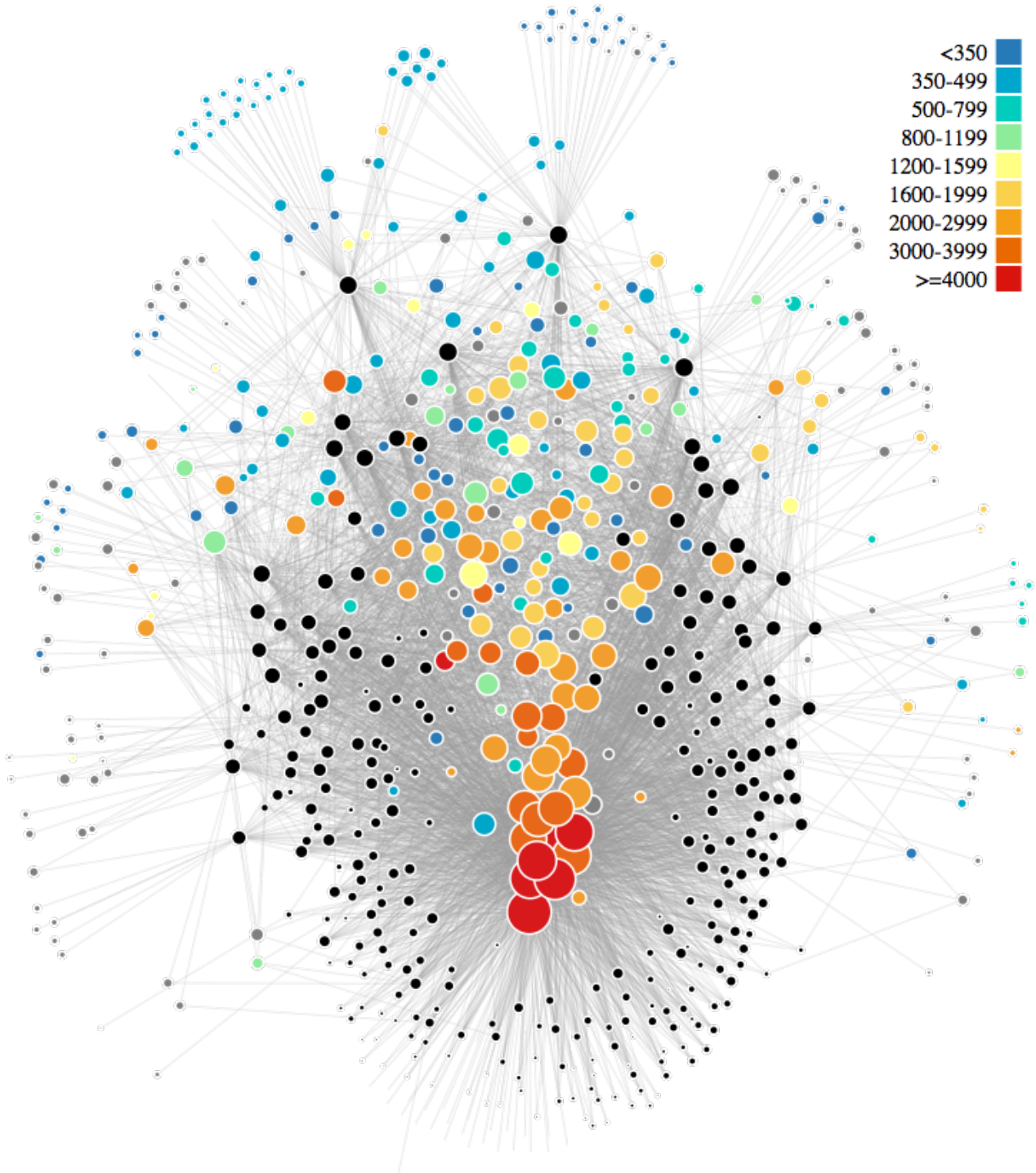
  - Size: mineral diversity

1. Biosignature
2. Embedded timeline

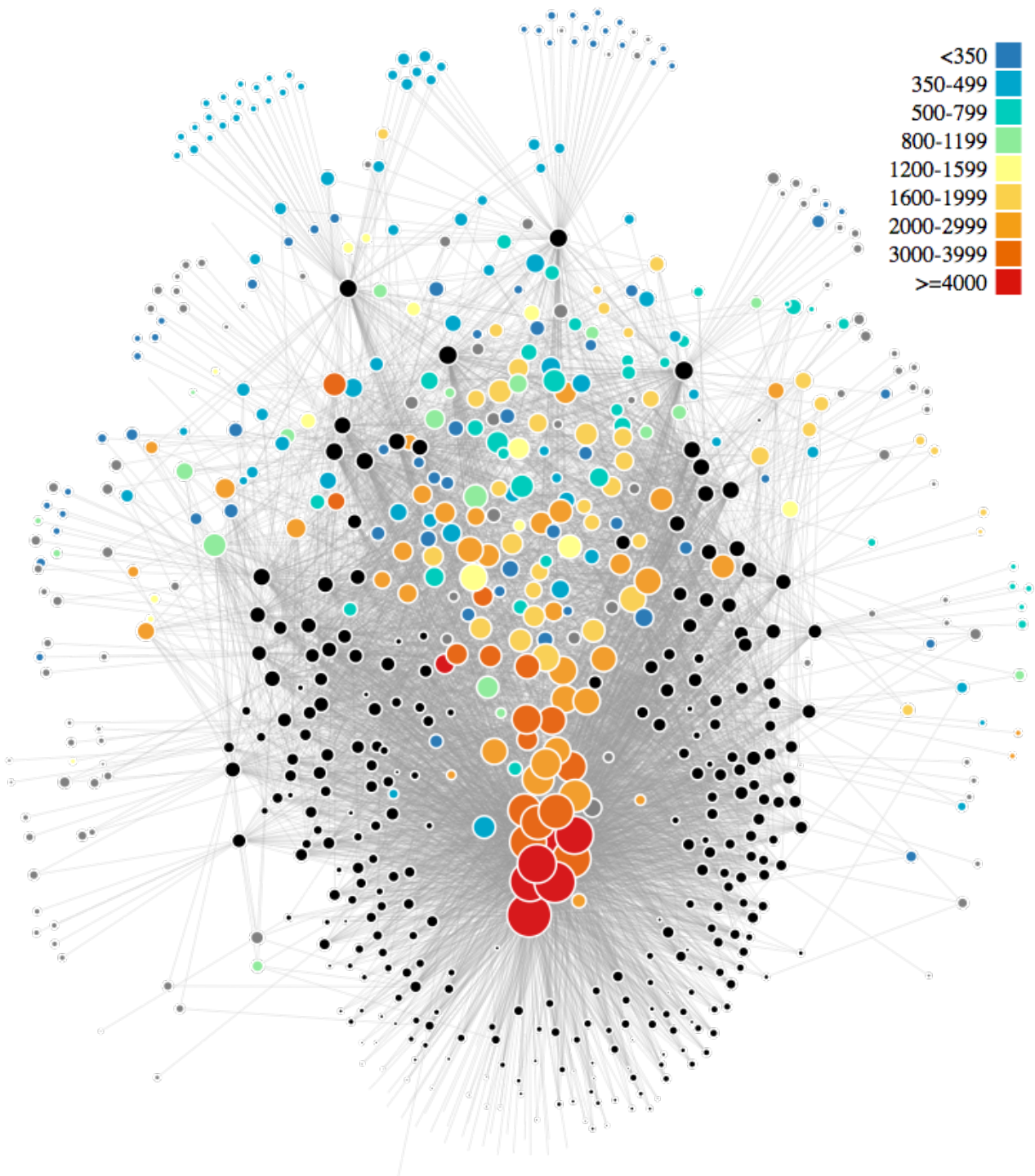
Hazen et al. 2019; Morrison et al. 2019



1. Biosignature [Hazen et al. (2016)]

Mineral diversity and distribution

- Large Number of Rare Events (LNRE) distribution

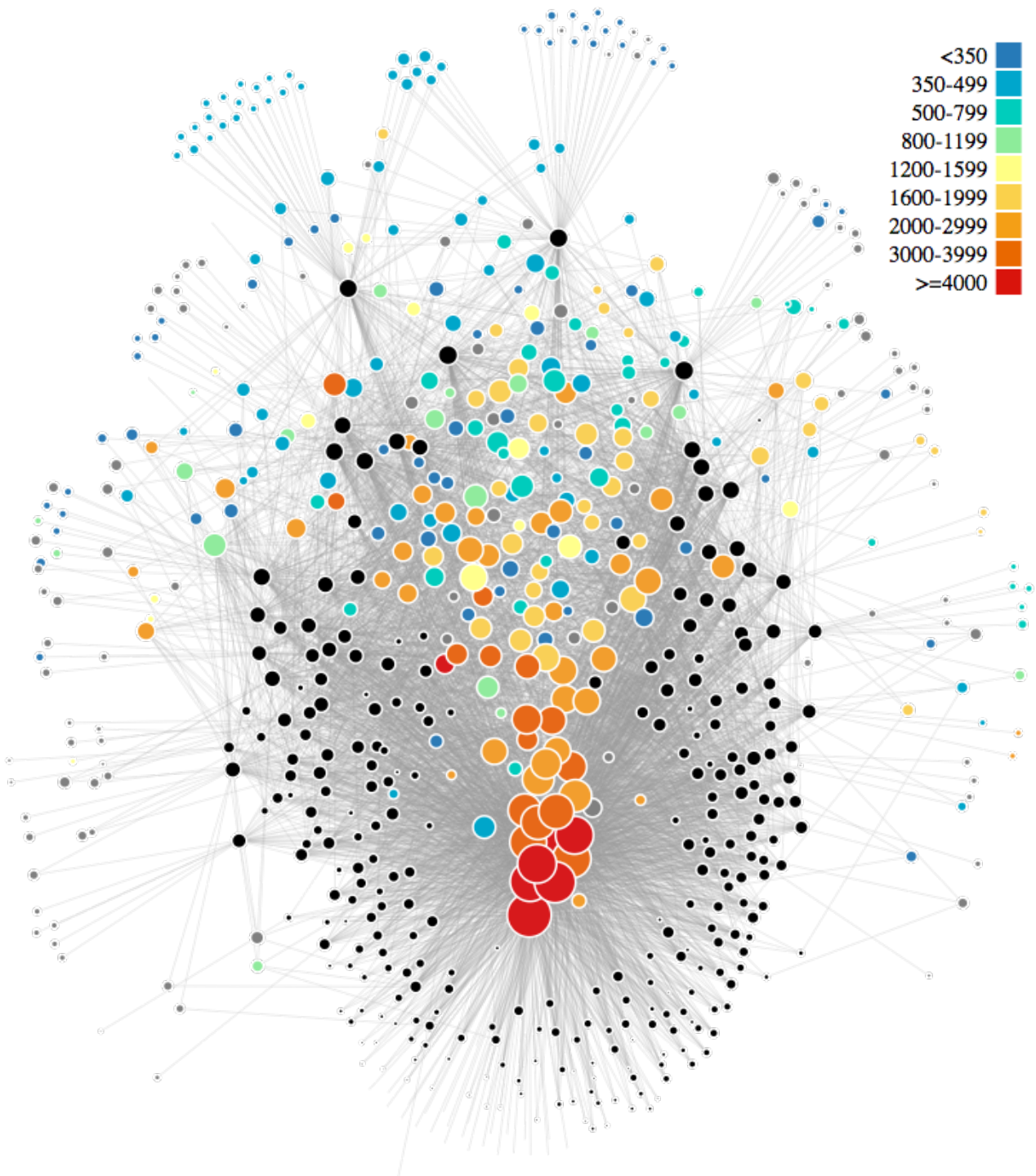


Hazen et al. 2019; Morrison et al. 2019

1. Biosignature [Hazen et al. (2016)]

Mineral diversity and distribution

- Large Number of Rare Events (LNRE) distribution
- High diversity (~5300 total)



Hazen et al. 2019; Morrison et al. 2019

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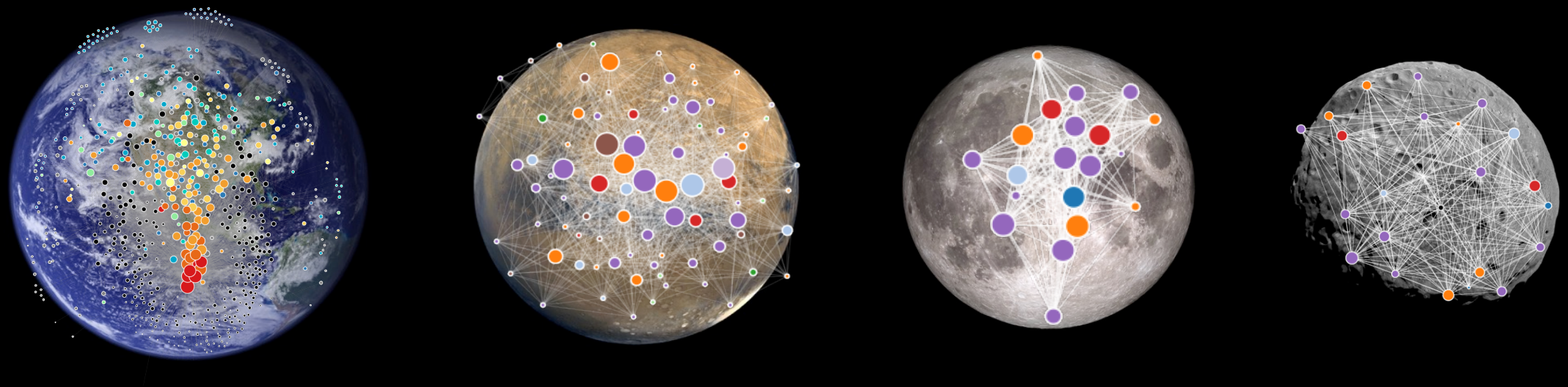
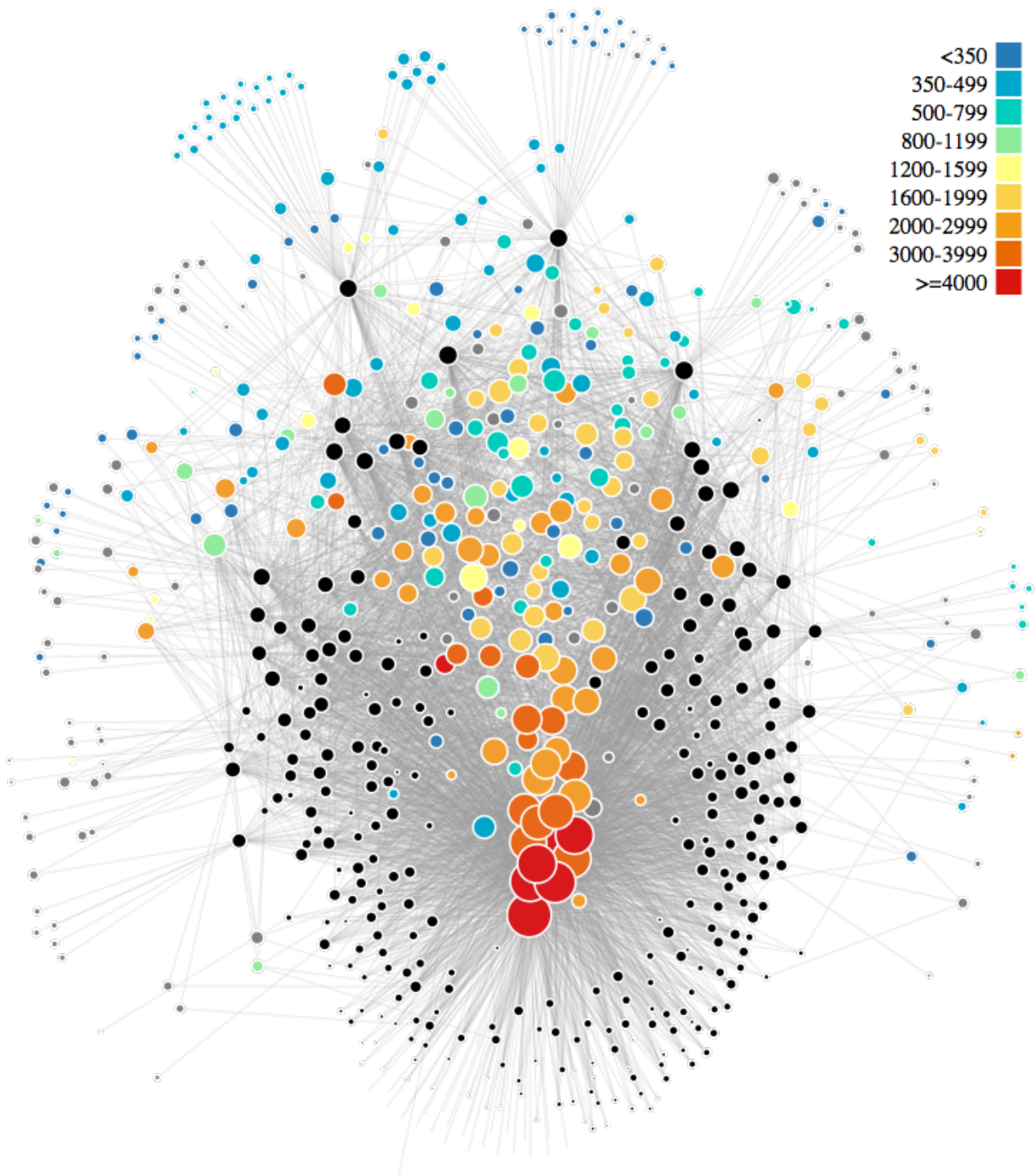


2. Embedded timeline

(In preparation: Muscente et al.)

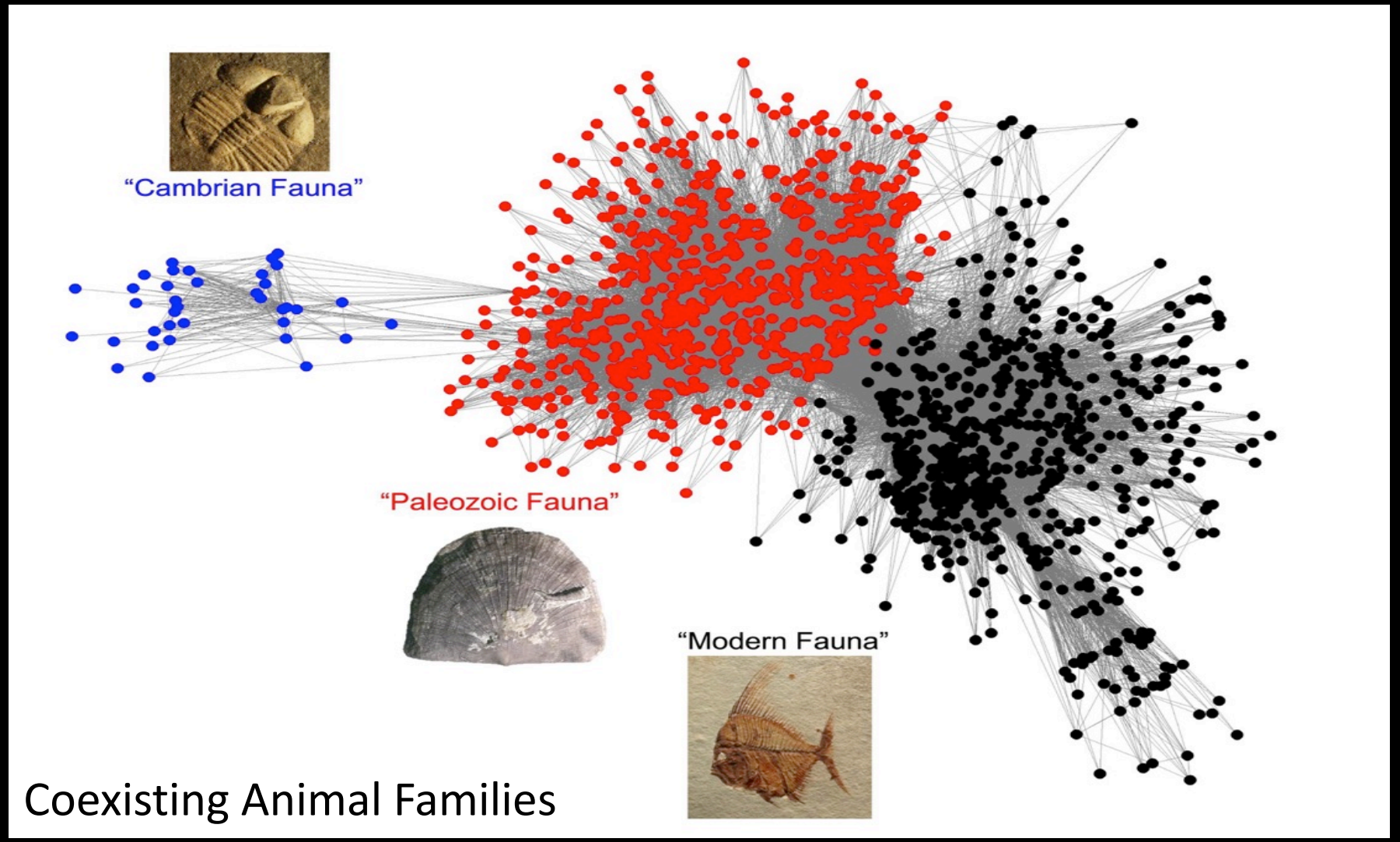
Nodes: colored by age



Hazen et al. 2019; Morrison et al. 2019

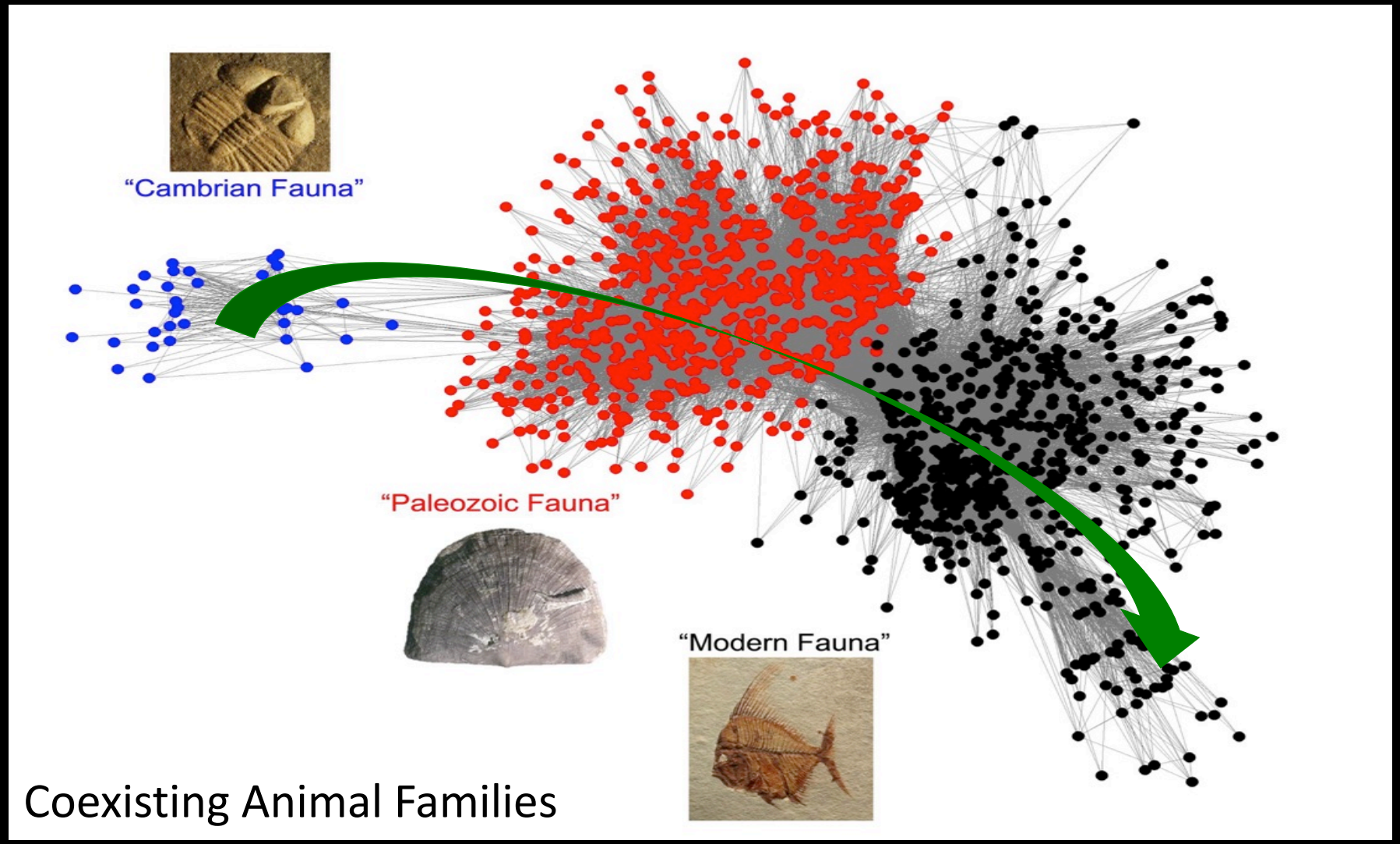
A. Prabhu

Paleobiology networks

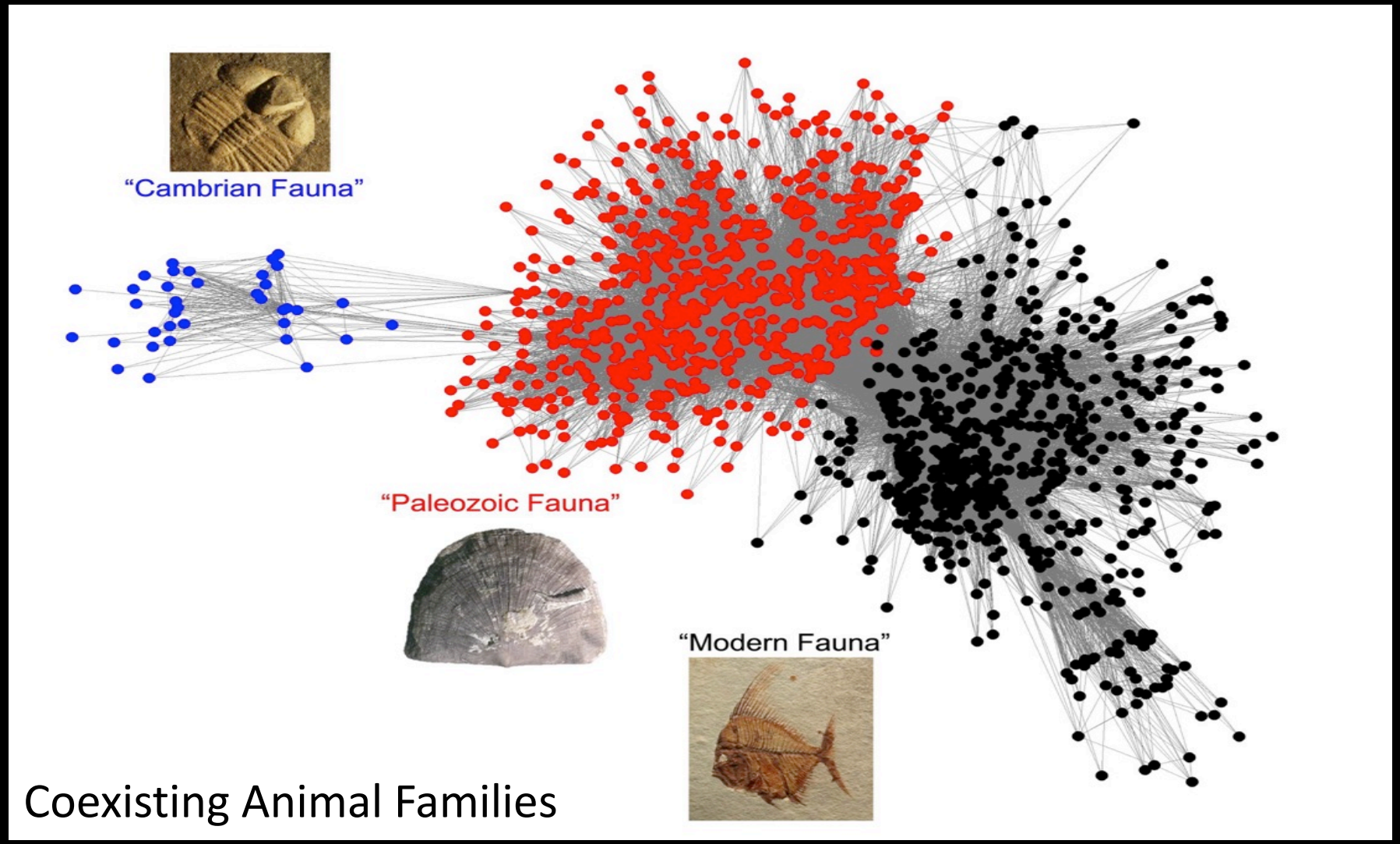


Coexisting Animal Families

Paleobiology networks

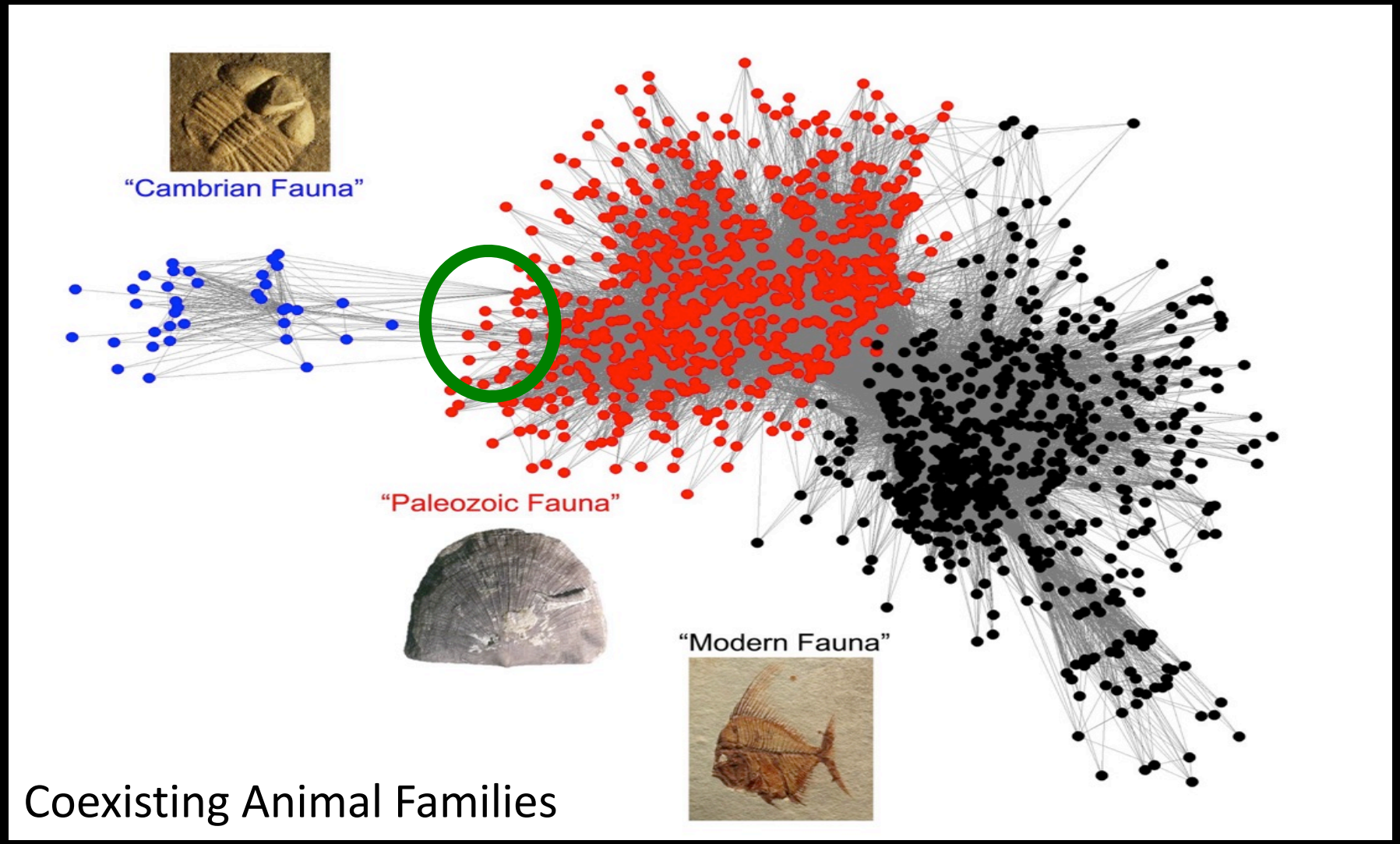


Paleobiology networks



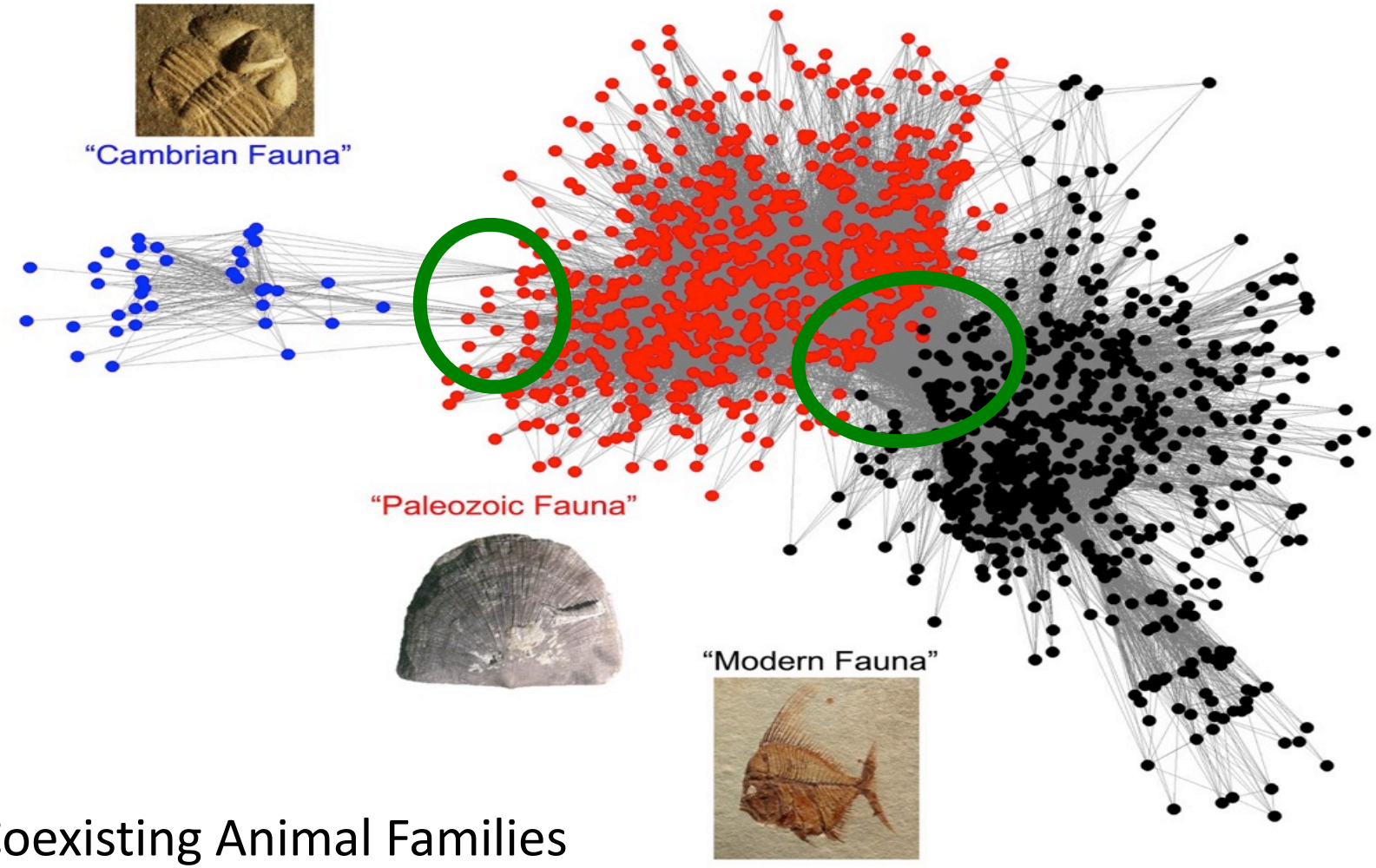
Coexisting Animal Families

Paleobiology networks



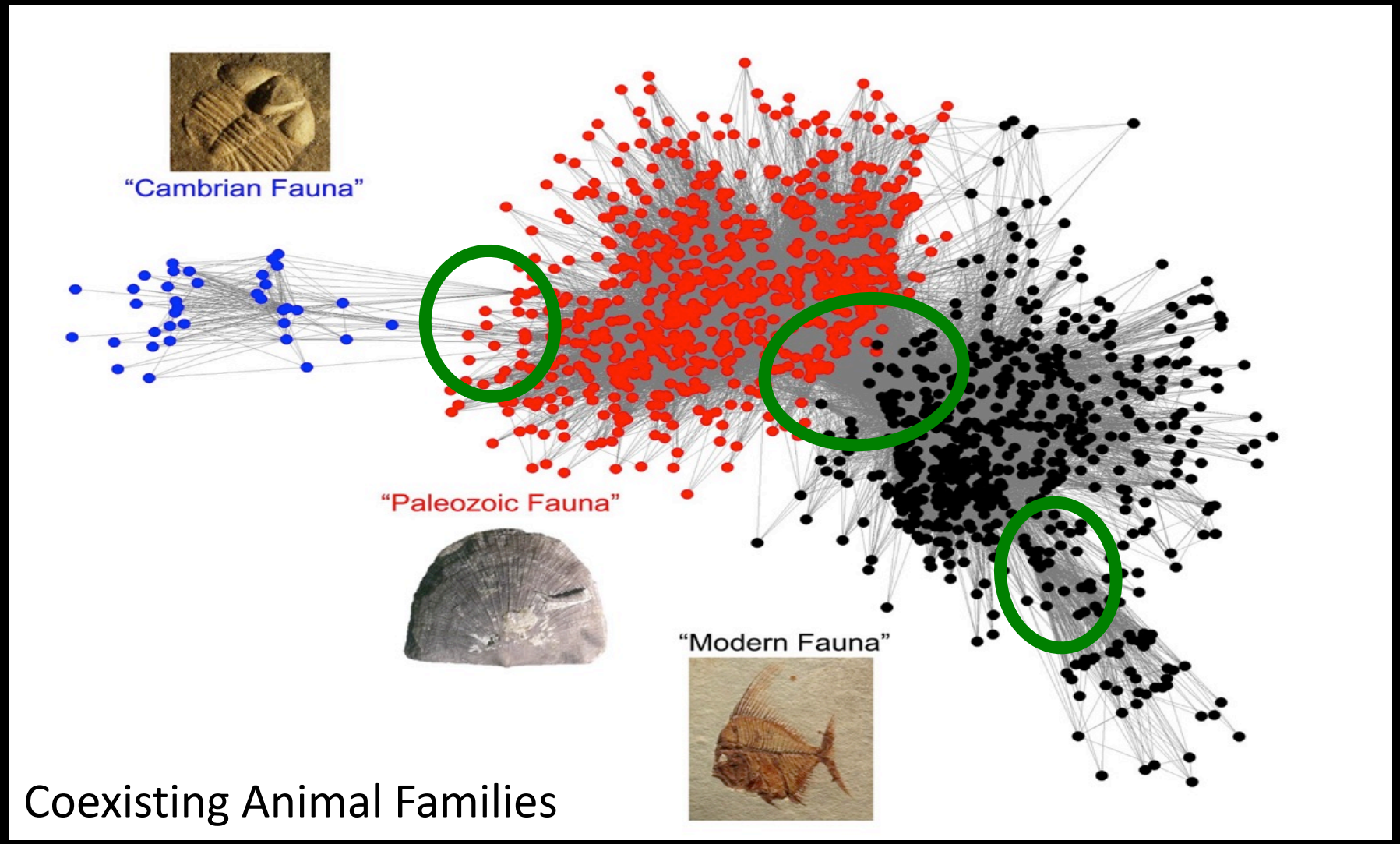
Coexisting Animal Families

Paleobiology networks



Coexisting Animal Families

Paleobiology networks

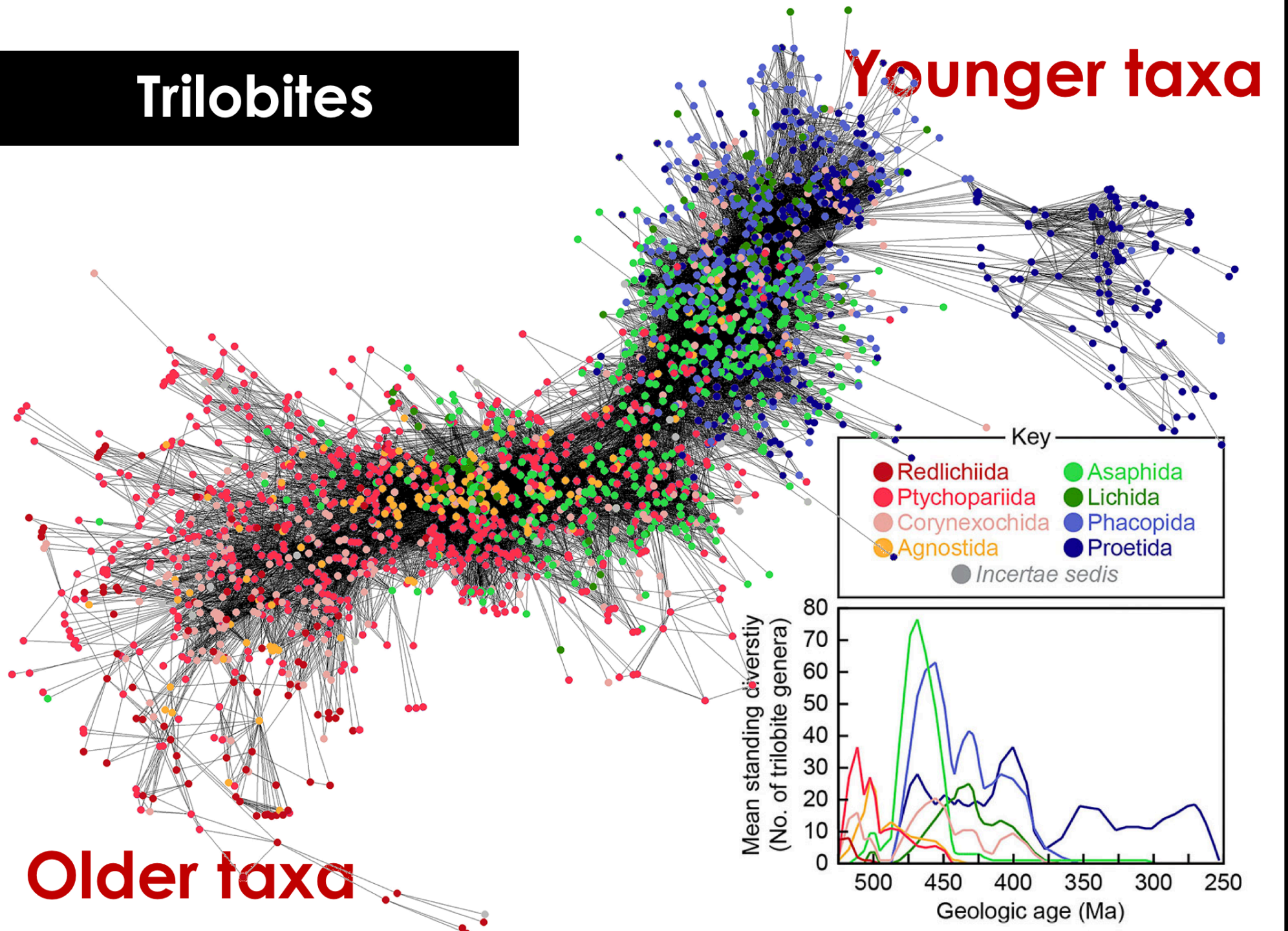


Coexisting Animal Families

Trilobites

Previously unrecognized mass extinction

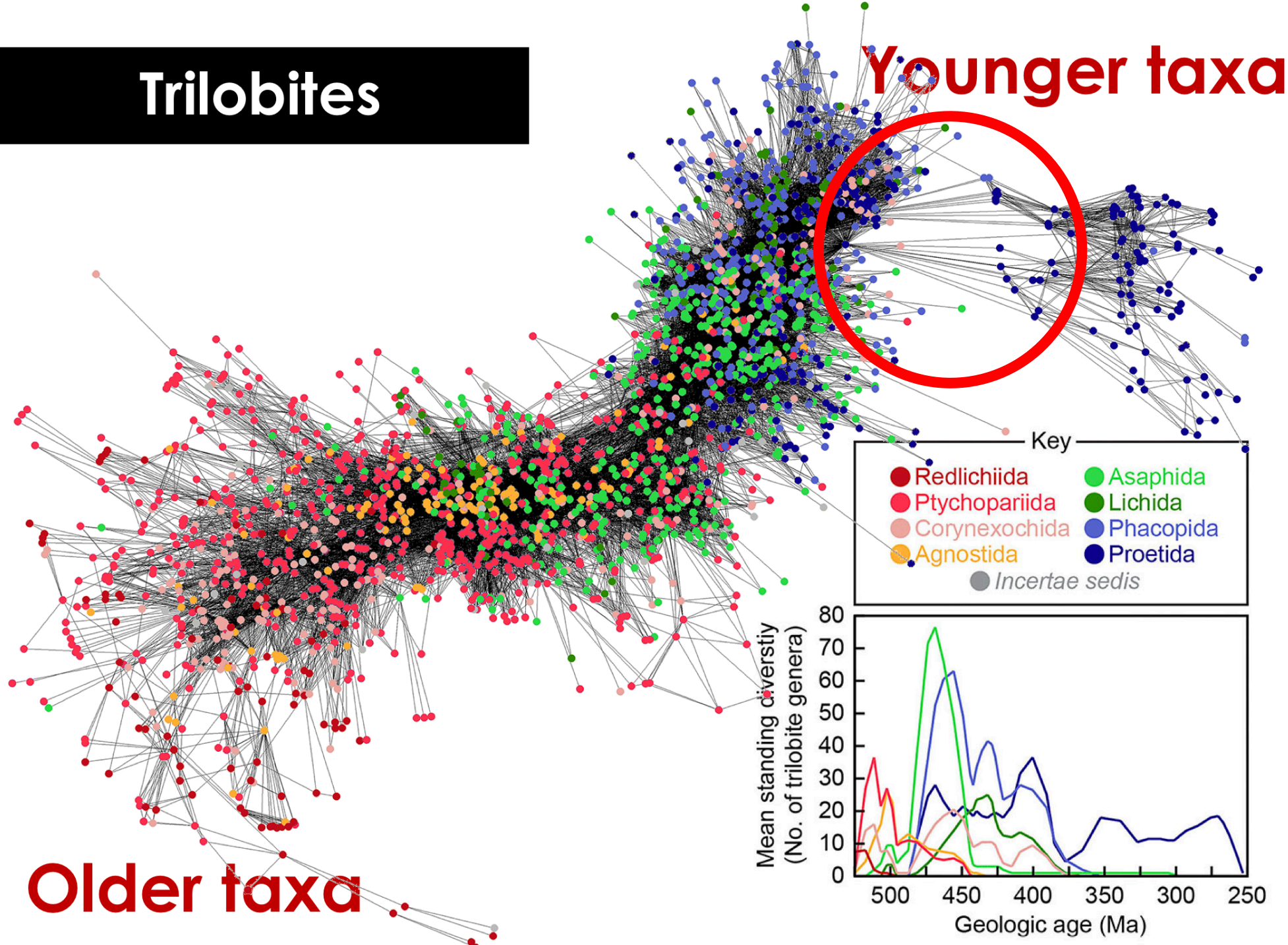
Drew Muscente



Trilobites

Younger taxa

Older taxa



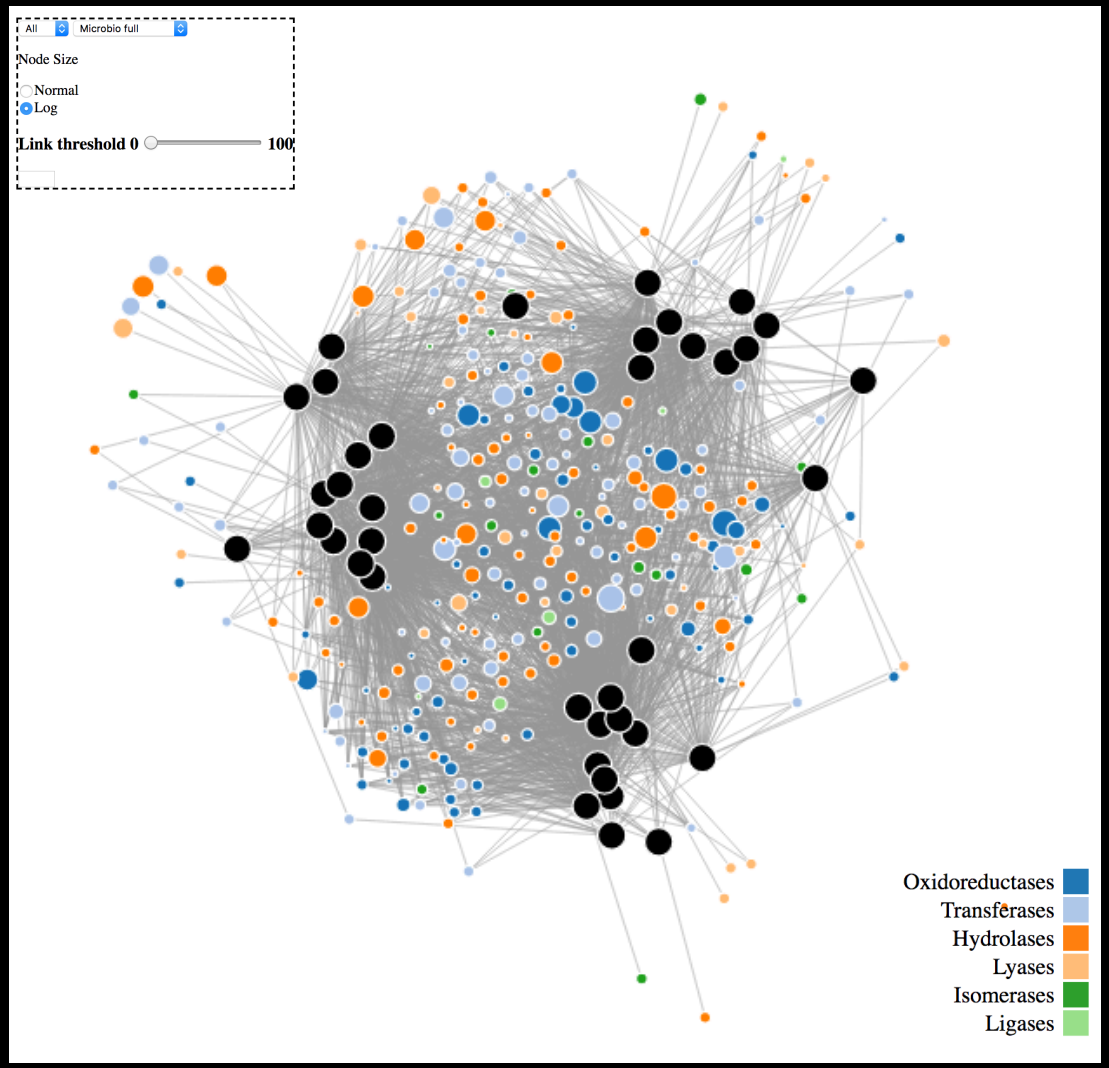
Previously unrecognized mass extinction

Drew Muscente

Data-driven projects and discoveries: Minerals vs Microbes

How did proteins co-evolve with their geologic environments?

Data-driven projects and discoveries: Minerals vs Microbes



Hazen et al. 2019; Buongiorno et al. In Prep

Questions

- Are microbial populations constrained by their geochemical environments?
- Did metal availability through deep-time effect protein evolution?

J. Buongiorno

D. Giovannelli

A. Eleish

R. Hazen

A. Prabhu

Data-driven projects and discoveries: Integrating with GPlates

What are the tectonic drivers and constraints on mineralization through deep time?

And what can this tell us about Earth's environments throughout history?

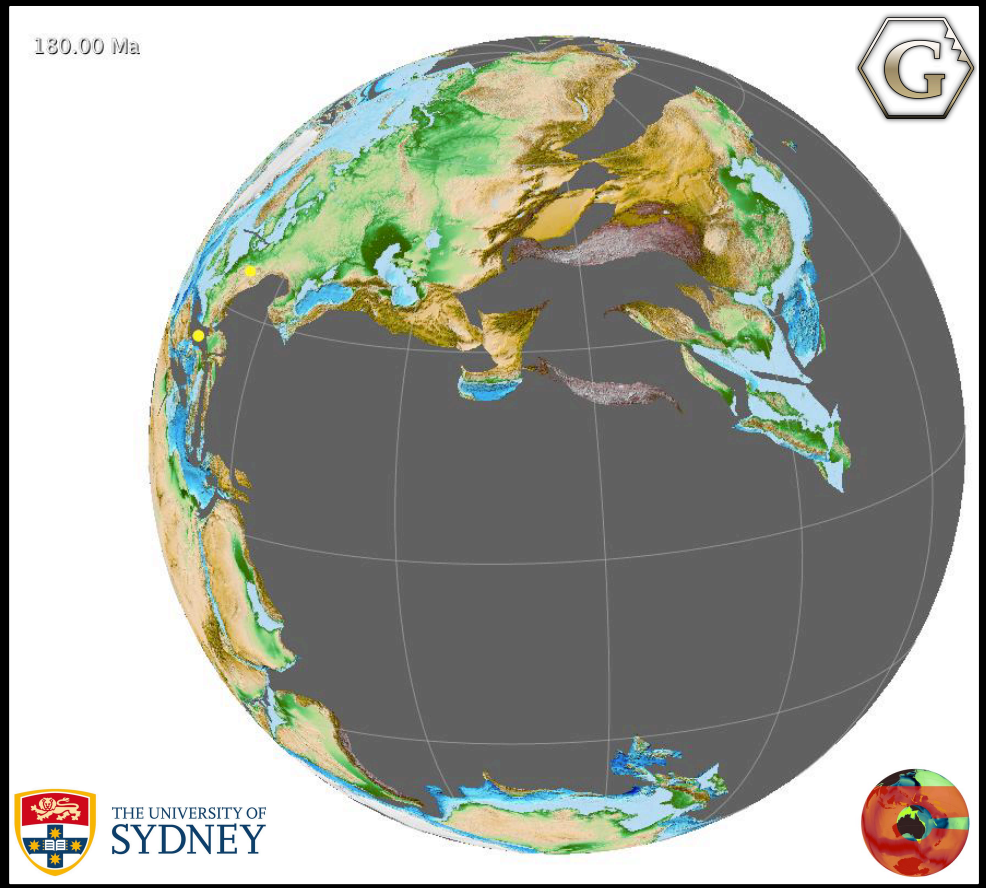
Dietmar Müller

Data-driven projects and discoveries: Integrating with GPlates

Sabin Zahirovic

Gplates: open-source paleotectonic reconstruction software that allows the user to interactively visualize tectonic and geodynamic models through deep time.

Yellow = Copper mineral
Black = Uranium mineral



earthbyte.org/gplates

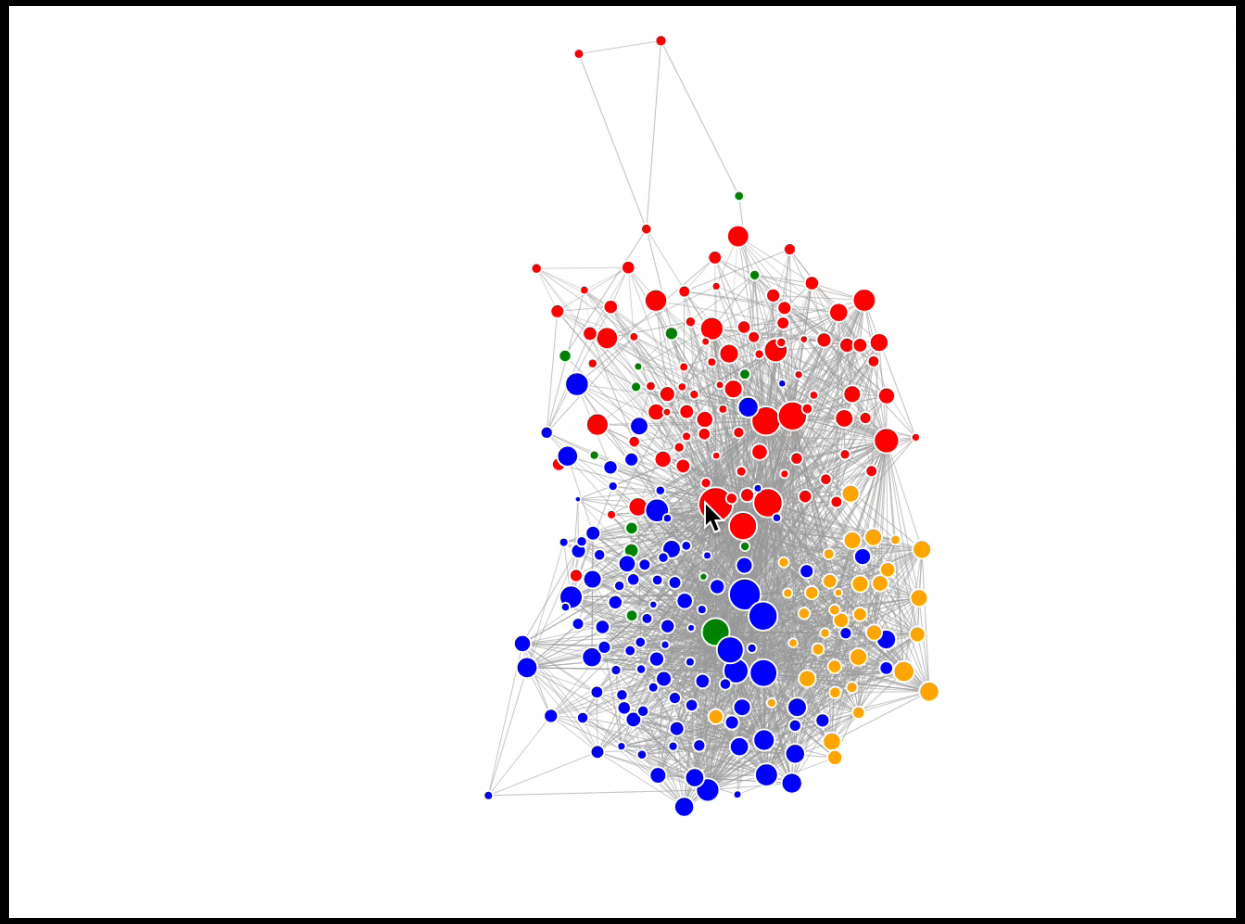
Morrison et al. 2019

Conclusions

Humans and other organisms are dramatically changing the mineralogical makeup of our planet.

Answering questions about complex, evolving systems and the materials within them requires multivariate, multidimensional approaches to integrating, visualizing, and analyzing cross-disciplinary data resources

Live networks: DTDI.carnegiescience.edu



Special thanks to:

W. M. Keck Foundation

Alfred P. Sloan Foundation

Deep Carbon Observatory

NASA Mars Science Laboratory Mission

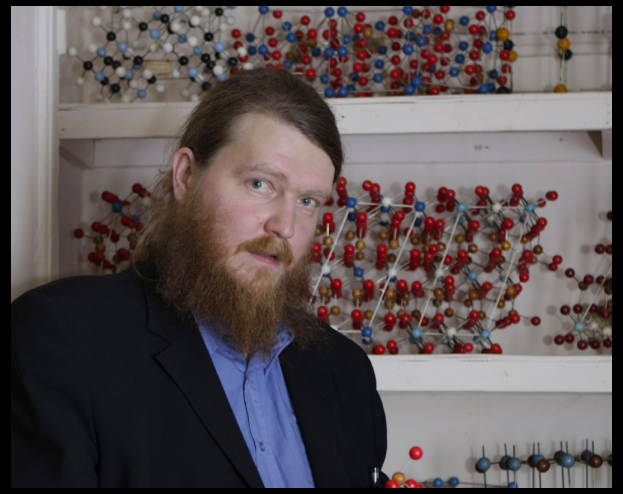
NASA Astrobiology Institute

National Science Foundation

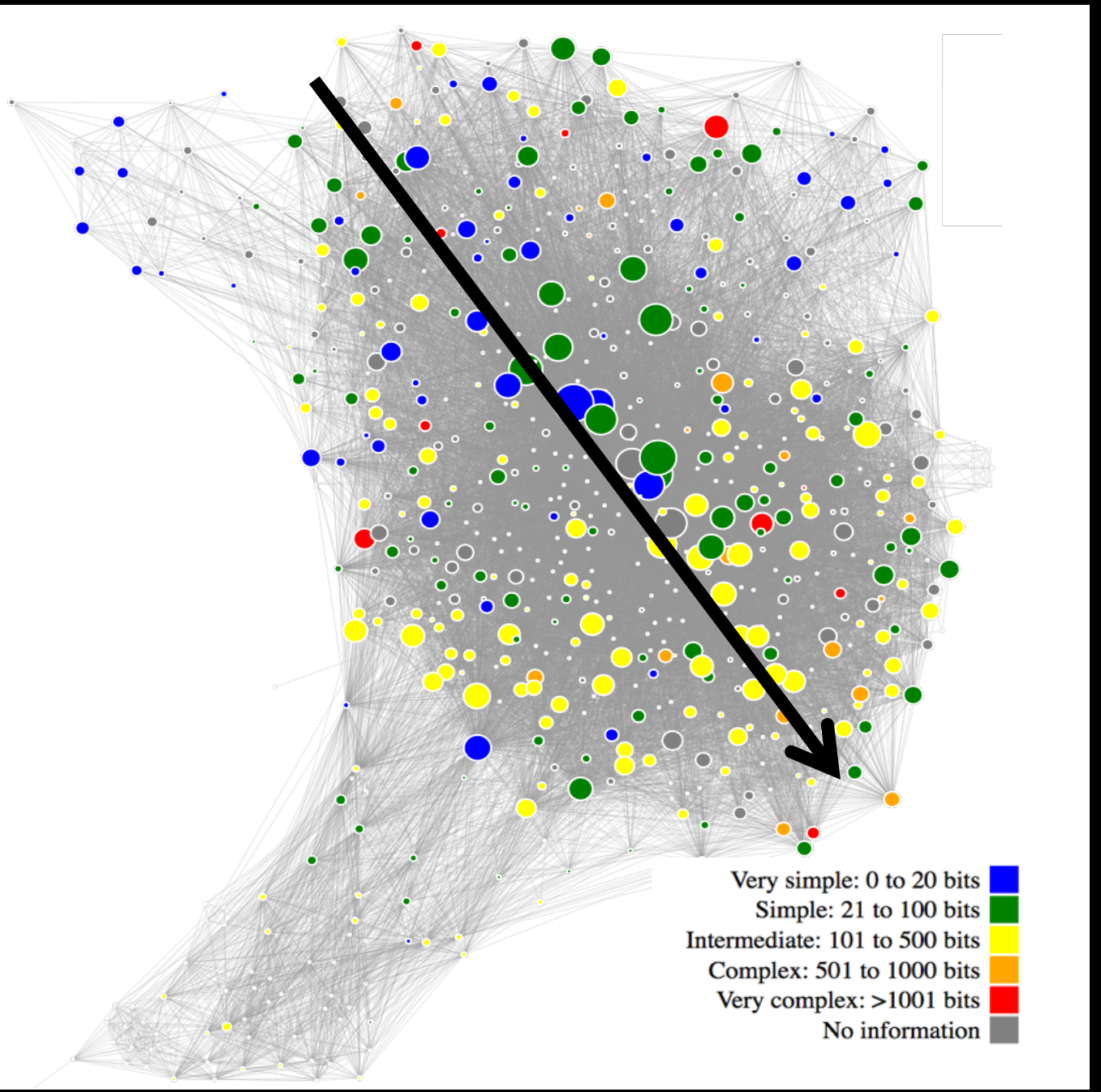
Backup slides

Cu mineral network

Structural Complexity



Sergey Krivovichev
Kola Science Center & SPbSU



Structural and chemical complexity of minerals: correlations and time evolution

Sergey V. KRIVOVICHEV[1,2,*], Vladimir G. KRIVOVICHEV[3] and Robert M. HAZEN[4]